



PHD

**Risk Factors for Injury in Elite Rugby Union
A Series of Longitudinal Analyses**

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RISK FACTORS FOR INJURY IN ELITE RUGBY UNION: A SERIES OF LONGITUDINAL ANALYSES

SEAN WILLIAMS

A thesis submitted for the degree of Doctor of Philosophy

University of Bath

Department for Health

January 2015

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ABSTRACT

The contacts and collisions that are inherent to elite Rugby Union, alongside changes to players' physical characteristics and match activities, have raised concerns regarding the level of injury burden associated with the professional game. This programme of research was therefore undertaken to investigate injury risk in this setting.

The first study of this thesis (Chapter 3) presents a meta-analytic review of injury data relating to senior men's professional Rugby Union, which shows an overall match incidence rate of 81 per 1000 player hours; this value is high in comparison with other popular team sports. In Chapter 4, the importance of injuries in the context of performance is demonstrated by showing a substantial negative association exists between injury burden and team success measures. Chapter 5 investigates subsequent injury patterns in this population and identifies injury diagnoses with a high risk of early recurrence, whilst also demonstrating that subsequent injuries are not more severe than their associated index injury. Playing professional Rugby Union on an artificial playing surface does not influence overall acute injury risk in comparison with natural grass surfaces (Chapter 6). Chapters 7 and 8 identify intrinsic risk factors for injury (previous injury, match and training loads) for the first time in this setting, and may be used to inform policies on these pertinent issues. Finally, predictive modelling techniques show some potential for predicting the occurrence and severity of injuries, but require further refinement before they can be implemented within elite Rugby Union teams.

Overall, this programme of work highlights the importance of injury prevention for all professional Rugby Union stakeholders, addresses the need to use appropriate statistical techniques to account for the dynamic and clustered nature of sport injury data, and demonstrates approaches through which the injury burden associated with elite Rugby Union may be reduced.

PUBLICATIONS

Williams, S., Trewartha, G., Kemp, S. & Stokes, K. (2013) A meta-analysis of injuries in senior men's professional Rugby Union. *Sports Medicine*, 43, 1043-1055.

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ABBREVIATIONS

ACL	Anterior Cruciate Ligament
AIC	Akaike Information Criterion
AU	Arbitrary Units
BIC	Bayesian Information Criterion
BMI	Body Mass Index
CI	Confidence Interval
ECR	Eurorugby Club Ranking
GPS	Global Positioning System
HR	Hazard Ratio
IRR	Incidence Rate Ratio
LCL	Lateral Collateral Ligament
LL	Log Likelihood
MCL	Medial Collateral Ligament
OSICS	Orchard Sports Injury Classification System
PCA	Principal Component Analysis
PCL	Posterior Cruciate Ligament
PH	Proportional Hazards
PRISP	Professional Rugby Injury Surveillance Project
RPE	Rating of Perceived Exertion
SD	Standard Deviation
SIC	Subsequent Injury Classification
SID	Subsequent Injury Definition
SMS	Short Message Service
VIF	Variance Inflation Factor

CHAPTER ONE

Introduction

1.1 Research overview

The game of Rugby Union is commonly believed to have originated from Rugby School, England, in 1823, and is now amongst the most played and watched sports in the world. The hosting of the Rugby World Cup in England in 2015, and the appearance of the shortened version of the game, Rugby Sevens, at the Rio 2016 Olympic Games, is expected to stimulate further growth and interest in the sport within the United Kingdom and internationally. However, since becoming a professional sport in 1995, Rugby Union has come under increasing scrutiny due to its perceived high risk of injury in comparison with other popular team sports (this perception has generally been supported by epidemiological literature). The introduction of professional full-time training, advancements in sports science and law changes have resulted in marked changes in players' physical characteristics (Sedeaud et al., 2013) and match activities (Quarrie and Hopkins, 2007). The result of such changes (e.g., more frequent collisions of greater magnitude) has brought into question the level of risk within the sport (Bourke, 2006), and these messages have been reflected in mainstream media (Kitson, 2014; Peters, 2014). Given that professional Rugby Union players are employed specifically to play matches, it is likely that the risk of injury in this setting would be deemed unacceptable when considered against standards used by regulators to assess risk in industrial and commercial sectors (Drawer and Fuller, 2002; Health and Safety Executive, 1995).

There is a legal and moral obligation for any employer to assess the risk of injury within their workplace, provide appropriate levels of information regarding that risk, and take preventative measures wherever possible. The recent litigation case involving the National Football League in America (Scheuerman, 2012) demonstrates that this responsibility very much applies to professional sport environments. The long-term consequences of participation in a sport must also be considered; injuries acquired through sporting careers may prevent physical activity, and thus health maintenance, during later life, and so investigations to understand and prevent the risk of injury during a professional athletes' playing career are

essential (Webbourn, 2012). Moreover, possible causal links between repetitive concussive episodes and neurodegenerative diseases have been proposed (Fuller et al., 2014) and so the long-term implications associated with a professional Rugby Union career may impact upon cognitive, as well as physical, aspects of health maintenance. Liability for the long-term consequences of sports injuries sustained during professional careers rests with clubs and governing bodies as employers.

In addition to the changing nature of player and match characteristics, it is often claimed that the high match and training demands placed on professional players are a contributing factor towards the high rate of injury in the English professional game. Indeed, newspaper articles in the English press have recently reported on the need for reduced match demands for professional players (e.g. James, 2014b; James, 2014a). Yet, investigations of the relationships between player load and injury have not been undertaken hitherto in this population. The changing nature of the game is also evidenced by the growing interest in the use of artificial playing surfaces, which have recently been introduced to the English Premiership. Such surfaces have numerous advantages, such as permitting greater usage and reducing maintenance costs for clubs. However, the influence that artificial playing surfaces have upon injury risk during professional Rugby Union matches is currently unclear, and so requires investigation. Beyond these critical player welfare and legal concerns, injuries have been associated with poorer team performance in other professional team sports (e.g. Hägglund et al., 2013). Highlighting a negative association between injuries and team performance may be important for communicating the significance of injury prevention to certain stakeholders (e.g. coaches). Injuries are likely to have a similar negative impact upon team success in Rugby Union, although no studies have been conducted to confirm this association. Clearly, injury surveillance and prevention is of the utmost importance for all professional Rugby Union stakeholders, as is the need to understand the wider impact of injuries within the sport.

In 1987, van Mechelen et al. presented the ‘sequence of prevention’, which is perhaps the most commonly cited model to framework sports injury prevention research. The model outlined a four step process for preventing sports injuries; firstly, the magnitude of the sports injury problem must be established. Secondly,

risk factors and mechanisms that are implicated in the injury risk must be identified. Then, strategies aimed at reducing the future incidence and/or severity of injuries are introduced. The final step is to assess the impact of those strategies by repeating step one. A number of epidemiological studies have described the incidence rate and nature of injuries within professional Rugby Union (see Chapter 3 for review). These studies have provided invaluable data regarding the overall risk of injury within Rugby Union, as well as the facets of the game that carry the highest risk. In some instances, rule changes have been instigated to help mitigate the injury risk. For example, the scrum was identified as having a high propensity to cause injury (Fuller et al., 2007b), and subsequent research led to a change in the engagement process, such that the biomechanical loading on players was reduced (Cazzola et al., 2014). However, overall there is a paucity of studies in elite Rugby Union populations that have moved beyond stage one of the ‘sequence of prevention’ model. In particular, few have identified modifiable intrinsic risk factors for injury. In other elite collision sports, such work has been shown to enable the prediction and prevention of injuries (Gabbett, 2010), which is the overarching aim of all injury epidemiology endeavours.

As well as preventing the initial occurrence of injuries (primary injury prevention), an important aspect of injury prevention programmes is to minimise the occurrence of subsequent injuries (secondary injury prevention), which have been associated with considerable burden in other professional team sports (Hawkins and Fuller, 1999; Rauh et al., 2007; Waldén et al., 2005). Classification schemes for recording subsequent injuries have been proposed, to aid the identification of causal relationships between injuries (Finch and Cook, 2013; Hamilton et al., 2011a). Yet, these schemes have not been implemented within elite Rugby Union studies to date.

The most recent sport injury model, proposed by Meeuwisse et al. (2007), highlights the need for studies to consider the changing nature of risk factors through time. In order to do so, statistical techniques that account for correlated outcomes (e.g. within individuals’ repeated events, or within teams), and allow for time-varying covariates are necessary (Liang and Zeger, 1993). To date, the use of such techniques within sports injury epidemiology, and in elite Rugby Union cohorts in particular, is scarce. As such, there is a clear need for studies incorporating these techniques to be

undertaken, in order to gain a full and accurate understanding of injury risk within this sport. Whilst a degree of injury risk will always exist in collision sports such as Rugby Union, there remains considerable scope to reduce the burden of injuries. To achieve this, prominent risk factors for injury must first be identified using methods that suitably account for the complex nature of such data.

The England Professional Rugby Injury Surveillance Project (PRISP) was first commissioned by the Rugby Football Union and Premier Rugby Limited in 2002, to conduct injury surveillance across all Premiership and England teams. The PRISP is now conducted annually, and is the world's largest study of professional Rugby Union injuries and training practices. These longitudinal data, detailing players' injury history and playing exposure using consistent methodology, provide an excellent platform for investigating risk factors for injury in this population. Based on the aforementioned background, this work was commissioned and funded by the Rugby Football Union and University of Bath to investigate the associations between a number of potential risk factors and injury risk in this population. Data collected across previous seasons of the PRISP were collated, where appropriate, as part of this Ph.D. This injury database was upheld by the academic host institution of the PRISP. The overarching aim of this work was to produce research that could potentially inform practice and lead to a reduction in injury burden within the sport.

Accordingly, the following research questions will be addressed:

- i. What is the overall level of injury risk within elite Rugby Union, and which facets of the game carry the greatest risk?
- ii. Is there an association between injuries and team success in elite Rugby Union?
- iii. How are subsequent injuries distributed within an elite Rugby Union population, and are there injury diagnoses with an increased risk of early recurrence?
- iv. What influence does an artificial playing surface have upon injury risk during elite Rugby Union matches?

- v. What influence do previous injury and match loads have upon injury risk in elite Rugby Union players, and is the frailty model an appropriate analysis strategy for this recurrent injury data?
- vi. Can predictive modelling techniques be used to predict the occurrence and severity of injuries in elite Rugby Union players?

1.2 Thesis overview

1.2.1 Chapter 2: Review of literature

A review of literature pertinent to the abovementioned research questions is provided in Chapter 2. This includes literature concerning the impact of injuries in sporting contexts, theories of injury causation and sports injury prevention, and methodological issues related to the recording, reporting and analysis of sport injury data. Additionally, risk factors for injuries in collision sports are discussed.

1.2.2 Chapter 3: A meta-analysis of injuries in senior men's professional Rugby Union

This chapter presented the first meta-analytic review of injury data relating to senior men's professional Rugby Union, in order to answer the first research question. The incidence rate, nature and severity of injuries in this population was summarised, and overall effects of level of play, new versus recurrent injuries, playing position, type of injuries, location of injuries, period of match and injury incident were determined.

1.2.3 Chapter 4: Association between injuries and team success in elite Rugby Union

An investigation of the association between injuries and team success is presented in Chapter 4. Linear mixed modelling techniques were used to assess the relationship between within-team changes, and between-team differences, in injury measures on markers of team success, and thus answer the second research question.

1.2.4 Chapter 5: Distribution and severity of subsequent injuries in elite Rugby Union: Application of the subsequent injury definition

Chapter 5 includes a study of subsequent injuries (i.e. those that succeed an initial injury) in this population, in order to answer the third research question. The distribution of such injuries is described, and the consequences of subsequent

injuries are compared with their associated index injuries for the first time within this population. Cluster analysis techniques were used to identify groupings within the data in relation to the time delay between index and subsequent (local and recurrent) injuries. Investigations of the risk of early recurrence for specific injury diagnosis groupings were also conducted.

1.2.5 Chapter 6: The influence of an artificial playing surface on injury risk and perceptions of muscle soreness in elite Rugby Union players

To determine the influence of an artificial playing surface on injury risk in this population (research question four), Chapter 6 presents the results of a prospective cohort study that compared the incidence rate and nature of both time-loss and abrasion injuries between games played on a third-generation artificial playing surface and natural grass surfaces. Perceptions of muscle soreness following games played on each type of surface were also compared, to determine how players respond to, and recover from, matches played on such surfaces.

1.2.6 Chapter 7: Previous injury and match load as risk factors for injury in elite Rugby Union players: Application of the frailty model for recurrent events

In Chapter 7, a frailty model is used to determine the influence that previous injury and match loads have upon injury risk in this population. The degree of correlation within repeated observations taken across individual players and teams was also examined, to determine the appropriateness of this analysis strategy. The results of this chapter were therefore used to answer the fifth research question.

1.2.7 Chapter 8: The development and application of injury prediction models in elite Rugby Union

To address the final research question, a study using predictive modelling techniques is presented in Chapter 8. This chapter consists of two parts; part one evaluates the efficacy of a machine learning model to predict the severity of injuries in this population, whilst part two presents an investigation of the relationship between training load measures and injury risk, and the efficacy of training load measures in predicting the occurrence of injuries. In part one, the predictive accuracy of the machine learning model was tested on an unseen dataset of injuries, and was compared with estimations made by medical staff. For part two, the principal

Chapter 1

components underlying the numerous training load measures were examined, and subsequently used to investigate their relationship with injury risk. Based upon the relationships identified between training load measures and injury risk in these analyses, an injury risk prediction model was then developed and evaluated.

1.2.8 Chapter 9: Discussion

A discussion of the key findings and conclusions of the thesis are presented in Chapter 9, in light of the research questions outlined in Section 1.1. The methodological approach adopted throughout the thesis, and the contribution made to existing knowledge, are also discussed. The practical implications of the findings and directions for future research are suggested.

CHAPTER TWO

Review of Literature

2.1 Overview

The purpose of this chapter is to summarise the literature that underpins epidemiological studies of Rugby Union injuries. Specifically, it will address literature pertaining to the impact, causation, and prevention of sporting injuries, as well as risk factors for injury in collision sports and methodological issues in sports injury studies. By doing so, it aims to provide a justification for undertaking the current research, and provide a detailed context within which the findings of the subsequent experimental chapters may be interpreted. Literature concerning the epidemiology (i.e., incidence rate, nature and severity) of injuries in elite Rugby Union populations will be systematically reviewed in Chapter 3, and so will not be addressed in this review of literature.

2.2 Injury epidemiology

Epidemiology is a branch of medicine that deals with the distribution and determinants of disease in human populations (Schootman and Albright, 1994). The epidemiological approach is based on the assumption that diseases do not happen purely by chance, rather there are causal and preventative factors that can be identified through the systematic investigation of populations (Gabriel, 2001). Injuries are known to share a number of similarities with diseases, and as such may be studied using epidemiological methods and principles (Gordon, 1949). The objective of injury epidemiology research is to reduce the risk of injury by quantifying the magnitude of the injury problem, understanding the causes and mechanisms of injury, and then implementing strategies to reduce those risks (Hlobil et al., 1987). This review of literature will focus on factors pertinent to epidemiological studies of Rugby Union injuries.

2.3 Impact of injuries in Rugby Union

Sporting injuries are one of the unwelcome consequences of participating in sport (Lower, 1995). The following section will address the various impacts that injuries may have for professional Rugby Union stakeholders.

2.3.1 *Player welfare*

Injuries result in a decline in sporting activity on a temporary or permanent basis, but of equal concern is the influence that injury experiences may have upon lifelong physical activity behaviour. Injuries acquired through sporting careers may prevent physical activity, and thus health maintenance, during later life through both catastrophic and degenerative mechanisms (Webborn, 2012). Moreover, the collisions and contact events inherent to Rugby Union are likely to increase the potential for such long-term implications in comparison with many other sports. An investigation of retired professional Rugby League players confirmed the presence of long-term consequences of injuries sustained during their playing careers, including job limitations, reduced income earning potential and increased personal medical costs (Meir et al., 1997). In amateur Rugby Union players, over a quarter of players were reported to have retired due to injury, with 35% of those who sustained an injury during involvement in a previous epidemiological study four years previously reporting significant effects on education, employment, family life and health (Lee et al., 2001a). An investigation of such effects in retired professional Rugby Union players, particularly those involved since the advent of professionalism, has not yet been undertaken, but would likely find similar, if not greater, long-term consequences of past injuries. Recently, attention has also been given to the possible neurological effects of repeated concussive incidents and head impacts. In particular, concerns regarding the possible increased risk of depression (Kerr et al., 2012), chronic traumatic encephalopathy (Gardner et al., 2014) and Alzheimer's disease (Mortimer et al., 1991) have been raised, but research concerning these topics is currently in its infancy, particularly with regards to Rugby Union cohorts. Elsewhere, complications associated with the regular use of painkillers and non-steroid anti-inflammatories (Malcolm et al., 2001), and the risk of premature degenerative disease of the cervical spine in front-row forwards (Trewartha et al., 2014), have also been highlighted amongst some of the potential long-term consequences of participation in Rugby Union.

Liability for the aforementioned long-term health consequences of participation in professional Rugby Union will lie with clubs and sporting bodies as the employers of those players. Therefore, these parties have a legal and moral obligation to monitor the risk of injury, provide appropriate levels of information regarding that risk, and

take preventative measures wherever possible (Fuller, 1995). The recent litigation case involving the National Football League in America (Scheuerman, 2012), who were accused of withholding information concerning the risks of playing American Football, confirms this clear legal perspective of sport injury epidemiology.

2.3.2 *Team success*

Beyond these important player welfare and legal perspectives, injuries in professional sports may have further impacts. A growing body of literature has demonstrated a clear negative association between injuries and team success in professional football cohorts (Arnason et al., 2004a; Eirale et al., 2013; Häggglund et al., 2013). That is, teams who lose fewer days to injury typically tend to outperform those with a higher burden of injury. Absences due to injury will likely prevent a coach from selecting the best team for a given match. Moreover, an inability to train will result in the diminishment of a player's fitness, strength and skill, which may subsequently negatively impact on team success. There may also be negative psychological effects (for the injured player and/or the team) associated with injury incidents (Ivarsson et al., 2013; Lavalley and Flint, 1996). Injuries that occur within a given match are also likely to reduce the team's chance of winning that fixture, as the strongest team is typically selected to play, so an injury to any player will weaken the team (Ekstrand et al., 2004b). Additionally, an injury may require a team to alter their tactical strategy, and may result in players playing out of their favoured position, both of which could reduce the team's chance of winning. Importantly, as casualty cannot be inferred from the studies that have investigated the relationship between injuries and team success, it may also be the case that a lower injury burden is the direct result of being successful. For instance, successful Rugby Union teams may be involved in fewer tackle situations over the course of a season (van Rooyen et al., 2014), or may have greater budgets available for medical, rehabilitation and strength and conditioning staff and services, both of which may attenuate their injury burden. To date, the association between injuries and team success has not been investigated in Rugby Union teams.

2.3.3 *Financial costs*

Since the advent of professionalism in Rugby Union, the commercial and financial elements of the sport have gained greater significance, and injuries may also impact

on this facet of the game. In professional football, the direct and indirect financial costs of injuries have been noted, including the cost of treatment and rehabilitation, the cost of acquiring a replacement player, the cost of reduced performance, the lost revenue from sponsors and supporters, and the cost of the injured players' wages (Drawer, 2001). It was therefore shown to be financially beneficial to prioritise the prevention of injuries in professional football (Drawer, 2001). All of the aforementioned costs will also apply to professional Rugby Union teams, and so the cost-benefit effect of effective injury prevention initiatives is also likely to be financially beneficial in this sport.

2.3.4 *Summary*

There are clear health, performance, financial and legal arguments for prioritising the prevention of injuries in professional sports. Given the higher rates of injury reported within Rugby Union compared with some team sports (e.g. professional football), these arguments may be especially pertinent. At present, however, there are no data addressing the association between injuries and team success in elite Rugby Union; evidence of a substantial association between injury measures and team success may be useful when attempting to communicate the importance of injury prevention to Rugby Union stakeholders, and when striving to implement injury prevention initiatives within an elite sport setting. Elsewhere, studies addressing the long-term implications of participating in elite Rugby Union are currently in their infancy. Nonetheless, the studies on this topic to date only serve to underline the importance of injury surveillance and prevention initiatives undertaken throughout a professional player's career.

2.4 **General theories of injury causation**

Injuries are typically considered to result from a transfer of energy to the tissue that exceeds the body's ability to maintain its structural and/or functional integrity (Fuller et al., 2007c; McIntosh, 2005). Four main theories have been proposed to explain such instances in non-sporting settings (Kumar, 2001), all of which have applications to sporting injuries. This section provides a brief overview of those theories.

2.4.1 *Multivariate interaction theory of musculoskeletal injury precipitation*

This theory states that injuries result from a complex interaction of various genetic, morphological, psychosocial and biomechanical factors, each of which have

numerous variables nested within them (Figure 2.1). An injury is hypothesised to result from an interaction between the relative weightings of the variables, and the extent to which these factors have been stressed within a given individual. As such, an injury may result from an infinite number of possible permutations of these variables. In a sporting context, these variables may refer to intrinsic (e.g. previous injury history) and extrinsic risk factors (e.g. exposure to high training and match loads), which interact to cause a level of strain (structural and/or physiological) that precipitates an injury.

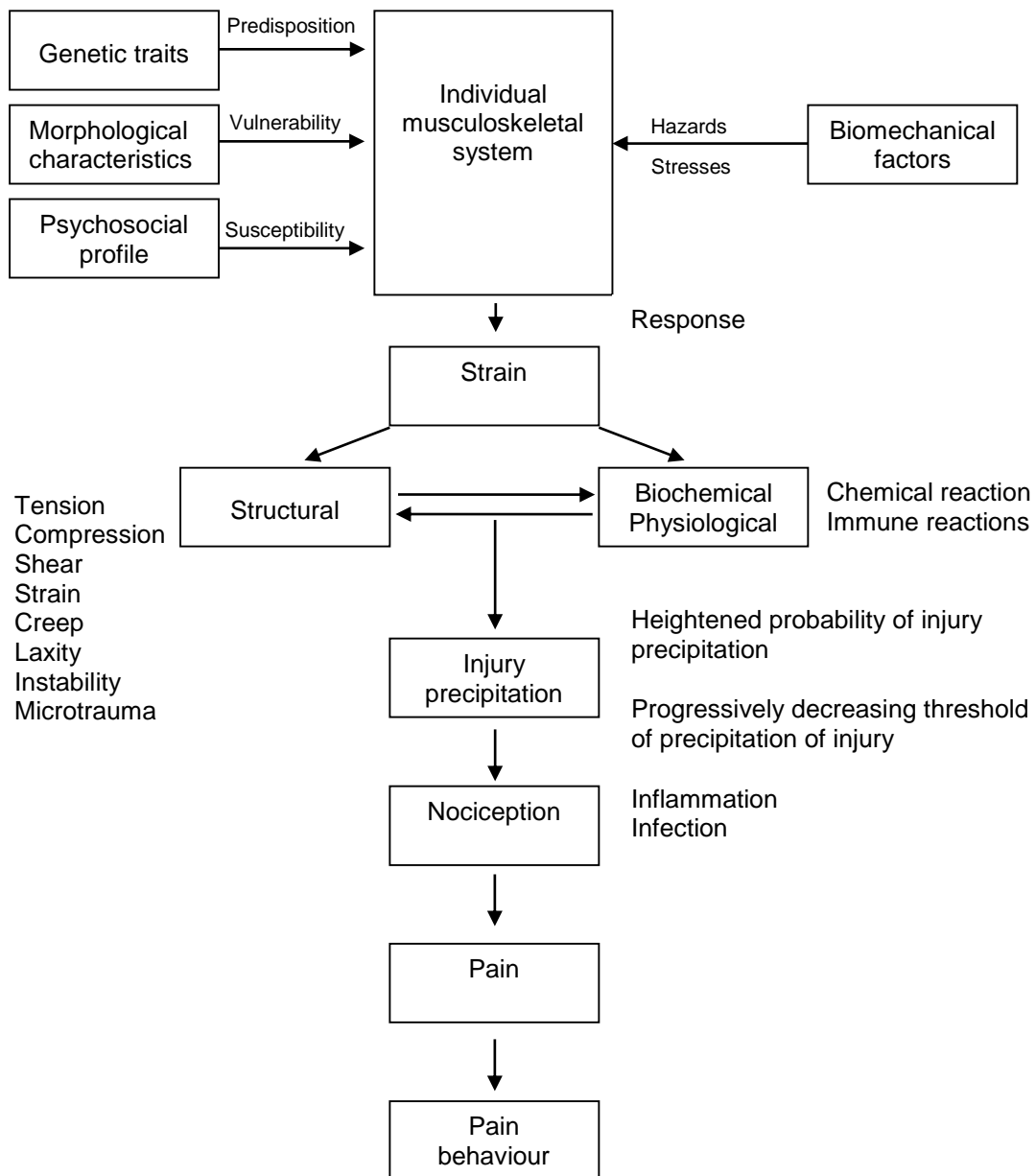


Figure 2.1 Multivariate interaction theory of musculoskeletal injury precipitation (Kumar, 2001). This model describes multi-factorial nature of the pathway to injury.

2.4.2 *Differential fatigue theory*

Many occupational tasks are repetitive in nature, and asymmetric motions are also common. The resultant differential, prolonged and repeated loading may elicit varying levels of fatigue in different muscles. Moreover, the muscles themselves are also likely to fatigue at varying rates, and this concept has been confirmed using electromyography studies (Kumar and Narayan, 1998). Differential fatigue may impact on two elements of the joint. Firstly, as fatigue develops, the muscles involved will be less able to generate force, which may lead to kinetic imbalances. Secondly, the connective tissue elements may be overloaded, leading to deformation and thereby interfering with the stability of the joint. Together, these imbalances may result in sub-optimal movement and loading patterns at a joint. The resultant stress generated may then lead to an injury. In a sports setting, this theory may be applicable to injuries that result from repeatedly-performed techniques (e.g. kicking injuries in Rugby Union).

2.4.3 *Cumulative load theory*

The cumulative load theory states that all biological tissues are subject to mechanical degradation with repeated and prolonged usage. The deformation of such tissues over time will typically lead to a reduction in their stress-bearing capacity, and the threshold at which they are liable to fail. This may explain why age (Section 2.8.1) and previous injury (Section 2.8.4) are commonly cited risk factors for injury in sporting populations. Experimental evidence to support this theory was presented by Kumar (1990), who demonstrated a strong association between cumulative load (biomechanical load associated with job tasks over working life) and low-back injury/pain (Figure 2.2).

2.4.4 *Overexertion theory*

As previously mentioned, injuries are typically considered to result from a transfer of energy to the tissue that exceeds the body's ability to maintain its structural and/or functional integrity (Fuller et al., 2007c; McIntosh, 2005). This 'overexertion' is a function of the force, duration, motion and posture of a given physical effort. The complex nature of these variables, as well as their various interactions, is described in detail by Kumar (1994). Briefly, this theory states that the force, effective exposure and postural load of a given activity interact to create a given level of risk

for that activity. If this level of risk exceeds the tissue level tolerance, then an injury is precipitated. This theory may be used to explain both acute and gradual-onset injuries; the former occurs when the tolerable force and/or strain rate of a given component is exceeded in a forceful exertion (e.g. contact injuries in Rugby Union), whilst the latter occurs when adequate recovery of a tissue is prevented as a result of the exertion and repetition of a given activity.

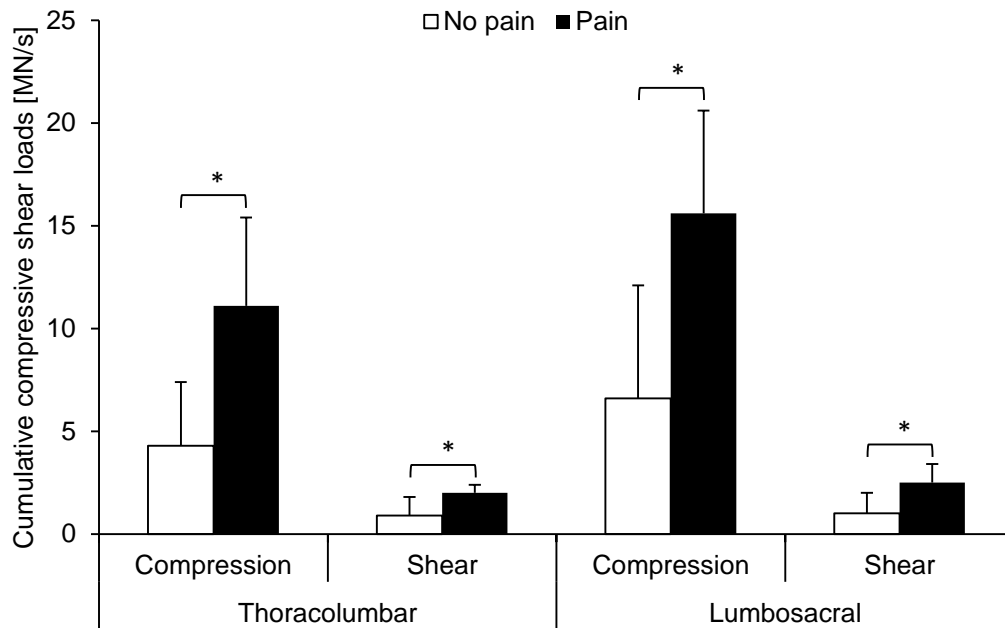


Figure 2.2 Mean cumulative compression and shear loads [MN/s] in ‘pain’ and ‘no pain’ groups in male sample. Data from Kumar (1990). Error bars represent standard deviations. *, statistically significant difference ($P < 0.05$).

2.4.5 Summary

Injuries may be considered to result from a transfer of energy to the tissue that exceeds the body’s ability to maintain its structural and/or functional integrity (Fuller et al., 2007c; McIntosh, 2005). The aforementioned theories describe the potential immediate mechanism of precipitation of injuries in non-sports settings, although these theories may also be used to explain the occurrence of sporting injuries. All four theories are likely to interact and operate simultaneously to modulate the occurrence of injuries to varying degrees.

2.5 Sport injury models

Sport injury models have been developed to provide a framework to the injury prevention process, and aid the understanding of the interaction between different

factors that lead to injuries in a sports setting. This section provides an overview of the key sport injury models in the extant literature. Models concerning the prevention of sporting injuries will be addressed first (Sections 2.5.1-2.5.2), followed by those that provide a framework for the pathway to sporting injury (Sections 2.5.3-2.5.5).

2.5.1 Sequence of prevention model

In 1987, van Mechelen et al. presented the ‘sequence of prevention’, which is perhaps the most commonly cited sports injury prevention model. The model outlined a four step process for sports injury prevention; firstly, the magnitude of the sports injury problem must be established. Secondly, risk factors and mechanisms that are implicated in the injury risk must be identified. Then, strategies aimed at reducing the future incidence and/or severity of injuries are introduced. The final step is to assess the impact of those strategies by repeating step one. Progress beyond step one of the ‘sequence of prevention’ model was initially limited within sports injury epidemiology literature (Chalmers, 2002), with intervention studies proving especially difficult to implement effectively in sports settings. Whilst advances have been made in recent years, there remains a large scope for improvement in this area (Klügl et al., 2010). Regulatory changes may represent one of the greatest opportunities for injury prevention in sports, but research in this area is underrepresented at present (Klügl et al., 2010).

2.5.2 Translating research into injury prevention practice framework

A further development to the ‘sequence of prevention’ model was provided by Finch (2006). The Translating Research into Injury Prevention Practice (TRIPP) framework added two further stages to the original van Mechelen four stage model. Stage five deals with understanding how the outcomes of the efficacy research in the previous four stages can actually be implemented in a real-world sport setting. The final stage in the TRIPP framework involves implementing the intervention in a real-world context, and then evaluating its effectiveness. Finch (2006) postulated these additional stages are necessary to ensure injury prevention measures are accepted, adopted and complied with by the cohort they are targeted at. The author (Finch, 2006) argues that if such considerations are not made, then injury prevention

measures are unlikely to be successful in reducing the incidence and/or severity of injuries in a real-world setting.

2.5.3 *Multifactorial model of aetiology*

Meeuwisse (1994) added to the sequence of prevention framework by attempting to account for the interaction of both internal and external risk factors, thus permitting the assessment of multiple risk factors and providing a more detailed framework for step two of the ‘sequence of prevention’ model. Specifically, the ‘multifactorial model of aetiology’ described how intrinsic predisposing factors, such as age, previous injury experience and sex, combine with an athlete’s exposure to extrinsic risk factors, such as a hard playing surface, to make the athlete susceptible to injury. Thereafter, an ‘inciting event’ is required for an injury to occur. The inciting event may be obvious in the case of acute injuries (e.g. a tackle or fall), but less apparent for overuse injuries that are the result of repetitive microtrauma. Bahr and Krosshaug (2005) emphasised the need to fully describe the inciting event in order to understand the causes of a particular injury type. In particular, these investigators describe a comprehensive model that accounts for the events leading up to the injury (playing situation, player and opponent behaviour), alongside a description of the global and detailed biomechanics at the time of injury. This model displays many similarities with the ‘multivariate interaction theory of musculoskeletal injury precipitation’ discussed in Section 2.4.1.

2.5.4 *A cyclical operational model to investigate contact sports injuries*

Gissane et al. (2001) recognised that a linear model, with a clear beginning (a healthy/fit athlete) and end point (an injury), may be too simplistic to describe the pathway to sports injuries. It was suggested that the ‘multifactorial model of aetiology’, described above, fails to account for the changing nature of intrinsic risk factors over time, and what happens to an athlete following an injury. The authors proposed a cyclical model that allowed healthy/fit athletes to return to sport, whilst also allowing for athletes to return to a lower level of play (Figure 2.3). The model starts with a healthy/fit player who will have a number of intrinsic risk factors. Then, with exposure to additional external risk factors, there is the potential for an injury event to occur. When an injury occurs, the ultimate outcome may be a return to sport

at the original level (thus completing the cycle), or a return at a lower level or even retirement from play.

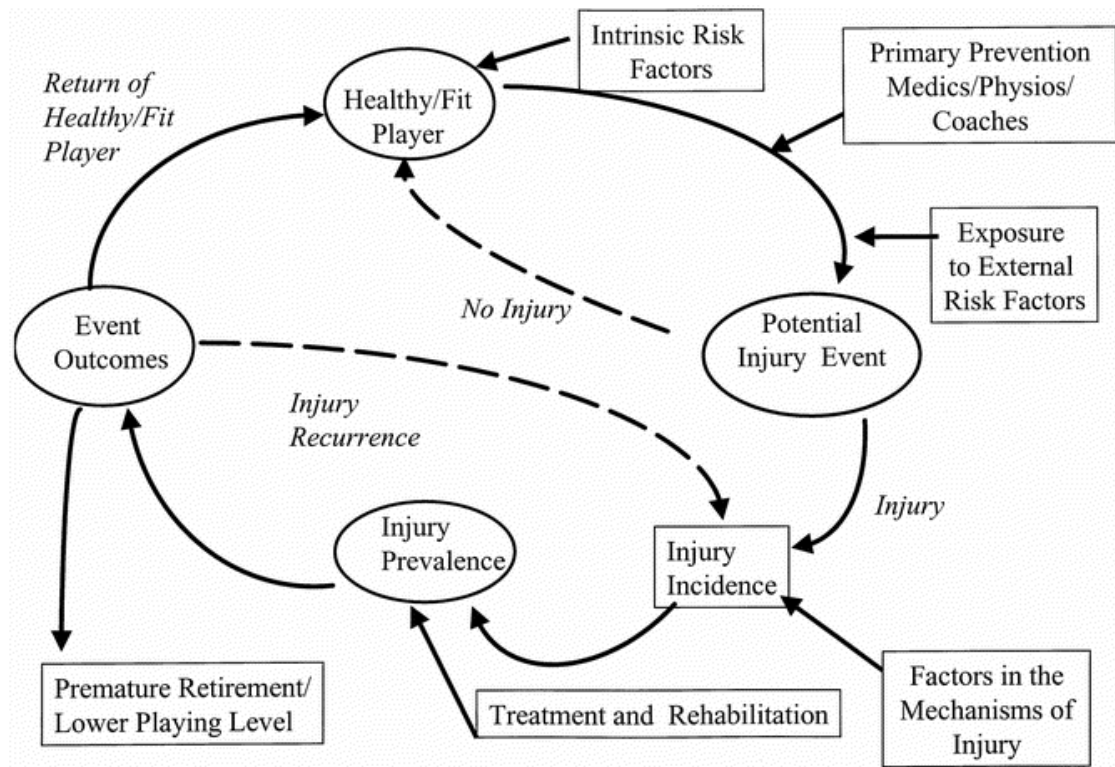


Figure 2.3 A cyclical operational model for the investigation of contact sports injuries (Gissane et al., 2001), which seeks to acknowledge the multifactorial and non-linear nature of injury pathways.

2.5.5 A dynamic, recursive model of aetiology in sport injury

Meeuwisse et al. (2007) have subsequently argued that the cyclical operational model proposed by Gissane et al. (2001) does not emphasise the adaptations that may have taken place following events both in the presence, and absence, of injury. Accordingly, Meeuwisse et al. (2007) developed an injury model that attempted to account for the recursive nature of risk and causation (Figure 2.4). This involved emphasising the fact that in sport, adaptations occur regularly both in the presence and absence of injury; these adaptations alter the future injury risk in a dynamic fashion. Meeuwisse et al. (2007) suggest that we must look beyond the initial set of risk factors, and instead consider how those risk factors may have changed in the preceding cycles of participation, whether linked with prior injury or not. The authors advocate the use of study designs and analysis strategies that allow the pattern of change in risk factors to be assessed, as opposed to the absolute value of the risk factor alone.

2.5.6 *Summary*

The pathway to injuries in a sports setting is complex, and several models have been developed to describe the interplay of factors, along with the overall process of injury prevention. Such models are invaluable for guiding the design and analysis of sports injury prevention studies, and providing a framework for their interpretation. The most recent models have emphasised the need for study designs and analyses that account for the changing nature of risk within individuals. Moreover, the importance of implementing research into practice effectively has been noted, so that real-world impacts may be achieved.

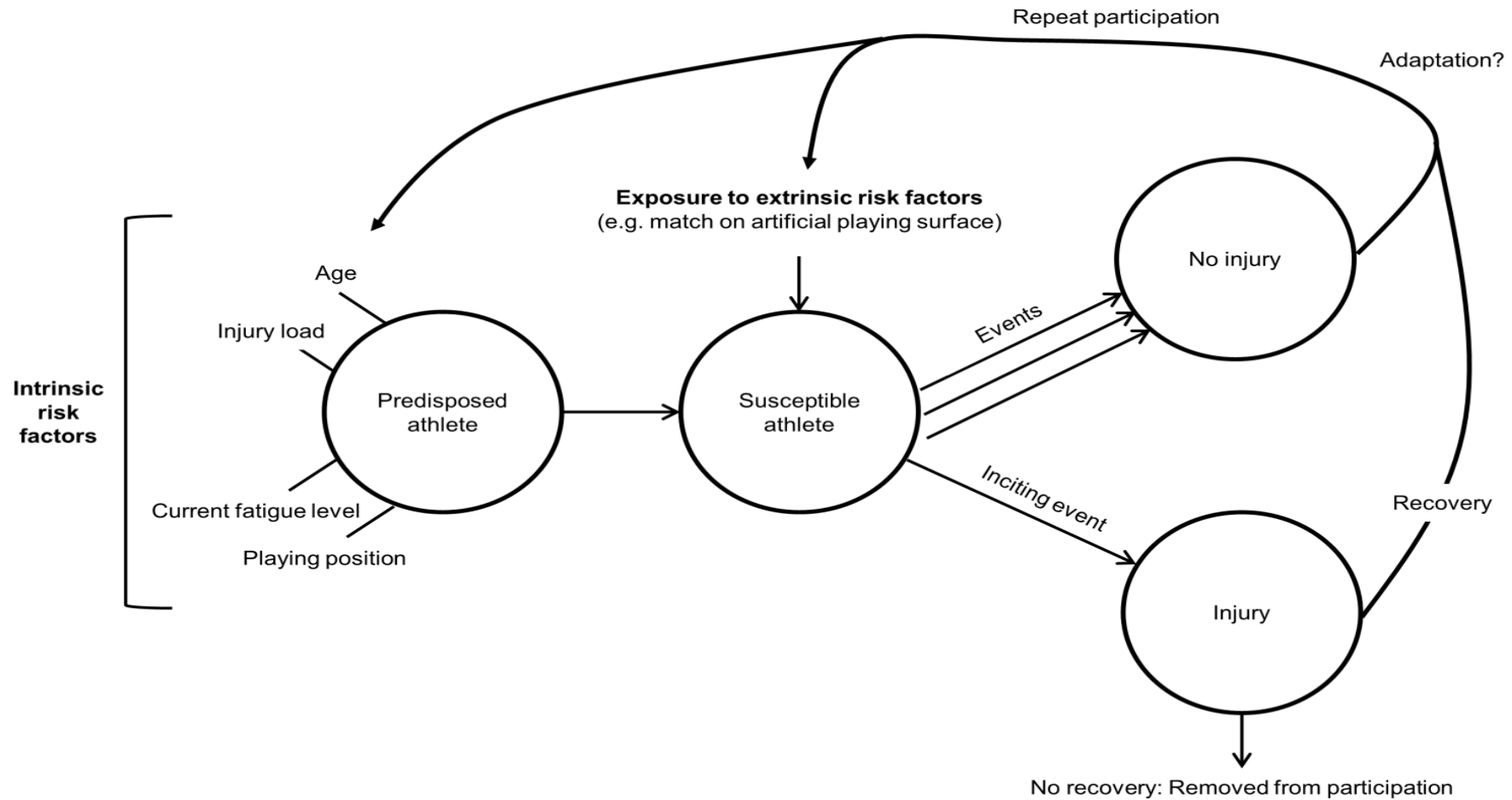


Figure 2.4 A dynamic, recursive model of aetiology in sport injury (adapted from Meeuwisse et al., 2007). This model highlights how susceptibility to injury is altered regularly, both in the presence and absence of injury events.

2.6 Methodological issues in epidemiology studies of sports injuries

A number of epidemiological study designs may be used for the investigation of risk factors for sports injuries, whilst numerous methods of reporting the results of such research may be adopted. The following section addresses the key methodological issues for conducting sports injury epidemiology research, with an emphasis on issues relevant to Rugby Union. In 2007, a consensus statement on injury definitions and data collection procedures for studies of injuries in Rugby Union was published (Fuller et al., 2007c); this section includes an overview of the key elements addressed in the consensus statement.

Study designs

2.6.1 Case-control studies

In a case-control study, the investigator starts with the classification of injury status and then collects information regarding prior exposure to specified risk factors (Schoutman and Albright, 1994). People with the outcome of interest (i.e. an injury) are matched with a control group who have not experienced that outcome (Mann, 2003). The strength of this study design is that they are relatively simple and economical to carry out (Wade, 1988b). However, as all case-control studies require retrospective recall of the participants' exposure history, there is a high potential for the exposure information to be biased (Kirby et al., 1981). Moreover, sampling bias may occur in either the 'cases' or 'control' groups (Mann, 2003).

2.6.2 Cross-sectional studies

In a cross-sectional study design, the investigator collects information concerning injury occurrence and exposure to risk factors from a cohort at one point in time (Schoutman and Albright, 1994). For example, Hoskins et al. (2009) used a cross-sectional approach to compare the lower back pain status in Australian football codes (soccer, Australian-rules, rugby league and Rugby Union) to non-athletic controls; a significant linear increase in lower back pain from the non-athletic group, to the semi-elite and elite groups was evident. Such studies have a high potential for recall bias, and their cross-sectional nature does not allow the temporal sequence between exposure and an outcome to be established (Aschengrau and Seage, 2003).

2.6.3 Cohort studies

In a cohort study, the investigator follows a group who are exposed to the activity of interest, such as Rugby Union, for a predetermined length of time during which the players will either sustain an injury, sustain no injury, or may be removed from the cohort for alternative reasons (e.g. a player may move to another club that is not involved in the study) (Aschengrau and Seage, 2003). This form of study design reduces recall bias, as injury information is collected proximal to the injury event (Bonita, 2006). Moreover, cohort studies provide the best assessment of the causal nature of a given factor on injury risk (Bonita, 2006). However, cohort studies are often expensive to run due to the requirement for large sample sizes and/or long follow-up periods (Aschengrau and Seage, 2003).

2.6.4 Intervention studies

In sports injury epidemiology, intervention studies are used to evaluate the effectiveness and safety of a strategy aimed at reducing the incidence of injury (Wade, 1988a). This is achieved by assigning two or more groups according to the study factor of interest (Schootman and Albright, 1994). For example, Kinchington et al. (2011) assigned one team of Rugby League players to a footwear programme intervention, while players from the control team continued to use self-selected footwear. The intervention consisted of footwear prescription, player education and frequent rotation of footwear. The intervention was effective in reducing the incidence rate of injuries (24.8 ± 2.2 per 1000 h) compared with the control group (30.8 ± 3.2 per 1000 h). Ideally, athletes should be randomly assigned to the intervention or control arm; this should result in the equal distribution of potential confounding factors, thereby removing their effect (Schootman and Albright, 1994). A well designed controlled trial, with appropriate randomisation to experimental and control conditions, provides the strongest evidence that a risk factor represented by the difference between treatments is responsible for a given injury risk (Hopkins et al., 2007). However, when evaluating the efficacy of certain interventions (e.g. protective equipment), it may not be feasible to randomly allocate participants to groups for logistical and/or ethical reasons (Gissane, 2003).

Reporting sport injury data

2.6.5 Injury incidence rates

In rugby injury epidemiology research, injury incidence rates (injuries per 1000 player hours) are the most common form of reporting injuries, where exposure time can either be match or training exposure (Fuller et al., 2007c). This method accounts for different levels of exposure between players/teams, and allows comparisons to be drawn between different sports (e.g. Brooks and Kemp, 2008) and across age groups (e.g. Bleakley et al., 2011). The consensus statement for injuries in Rugby Union uses the following definition of injury (Fuller et al., 2007c):

‘Any physical complaint, which was caused by a transfer of energy that exceeded the body’s ability to maintain its structural and/or functional integrity, that was sustained by a player during a rugby match or rugby training, irrespective of the need for medical attention or time loss from rugby activities. An injury that results in a player receiving medical attention is referred to as a ‘medical-attention’ injury and an injury that results in a player being unable to take full part in future rugby training or match play as a ‘time-loss’ injury.’

The consensus statement recommends that studies should not incorporate mixed definitions of injury; indeed, all Rugby Union injury studies published subsequent to the consensus statement have recorded ‘time-loss’ injuries only (e.g. Fuller et al., 2010b; Fuller et al., 2008; Fuller et al., 2009; Fuller et al., 2012a; Kemp et al., 2011; Takemura et al., 2011). While use of a ‘medical-attention’ injury definition would likely increase the volume of injury data captured, it would also be subject to serious theoretical and/or practical limitations (e.g. greater inter-club variation in data collection and reporting of injuries) (Orchard et al., 2007). Prior to the consensus statement, a variety of injury definitions had been used within the Rugby Union injury literature. For example, Bathgate et al. (2002) defined an injury as an event that forced a player to either leave the field or miss a subsequent game, while Holtzhausen et al. (2006) recorded all injuries that prevented playing or training, *or* that required medical attention. Such differences will have a direct impact on the injury incidence rate reported (Brooks and Fuller, 2006), and so often

preclude comparisons being drawn between studies. Elsewhere, the Accident Compensation Corporation in New Zealand, which provides compensation for all injury costs, allowed an alternative calculation of injury rates (injury claims per 100,000 players per year) over the course of a Rugby Union injury prevention programme in New Zealand (Gianotti et al., 2009).

2.6.6 *Injury severity*

Time (days) lost from competition and practice is accepted as a basis for defining the severity of an injury (Fuller et al., 2007c). Specifically, the consensus statement for injuries in Rugby Union defines the severity of an injury as:

‘The number of days that have elapsed from the date of injury to the date of the player’s return to full participation in team training and availability for match selection.’

Creighton et al. (2010) have developed a three step decision-based return-to-play model for sports injuries in an attempt to explain the decision making process that ultimately dictates the reported injury severity (Figure 2.5). In step one, medical factors relating to the injury are evaluated to determine the health status of the athlete. In step two, the clinician evaluates the participation risk, which is influenced by both the health status of the athlete and sport risk modifiers (e.g. playing position and ability to protect the injury). In step three, ‘decision modifiers’ are considered (e.g. desire of athlete to compete). This process is likely to be recursive, such that the evaluations are revisited as the rehabilitation progresses. All clinicians are likely follow such a process (either consciously or subconsciously) when making return-to-play decisions.

The consensus statement also recommends that injuries should be grouped based on their severities: slight (0-1 days); minimal (2-3 days); mild (4-7 days), moderate (8-28 days), severe (>28 days), “career-ending” and “non-fatal catastrophic injuries”. Prior to the publication of the consensus statement, there was substantial variation in how injury severity was graded. For instance, Garraway and Macleod (1995) defined all injuries of less than 28 days as ‘mild’, whilst Best et al. (2005) defined a ‘mild’ injury as those that resulted in a player missing one match.

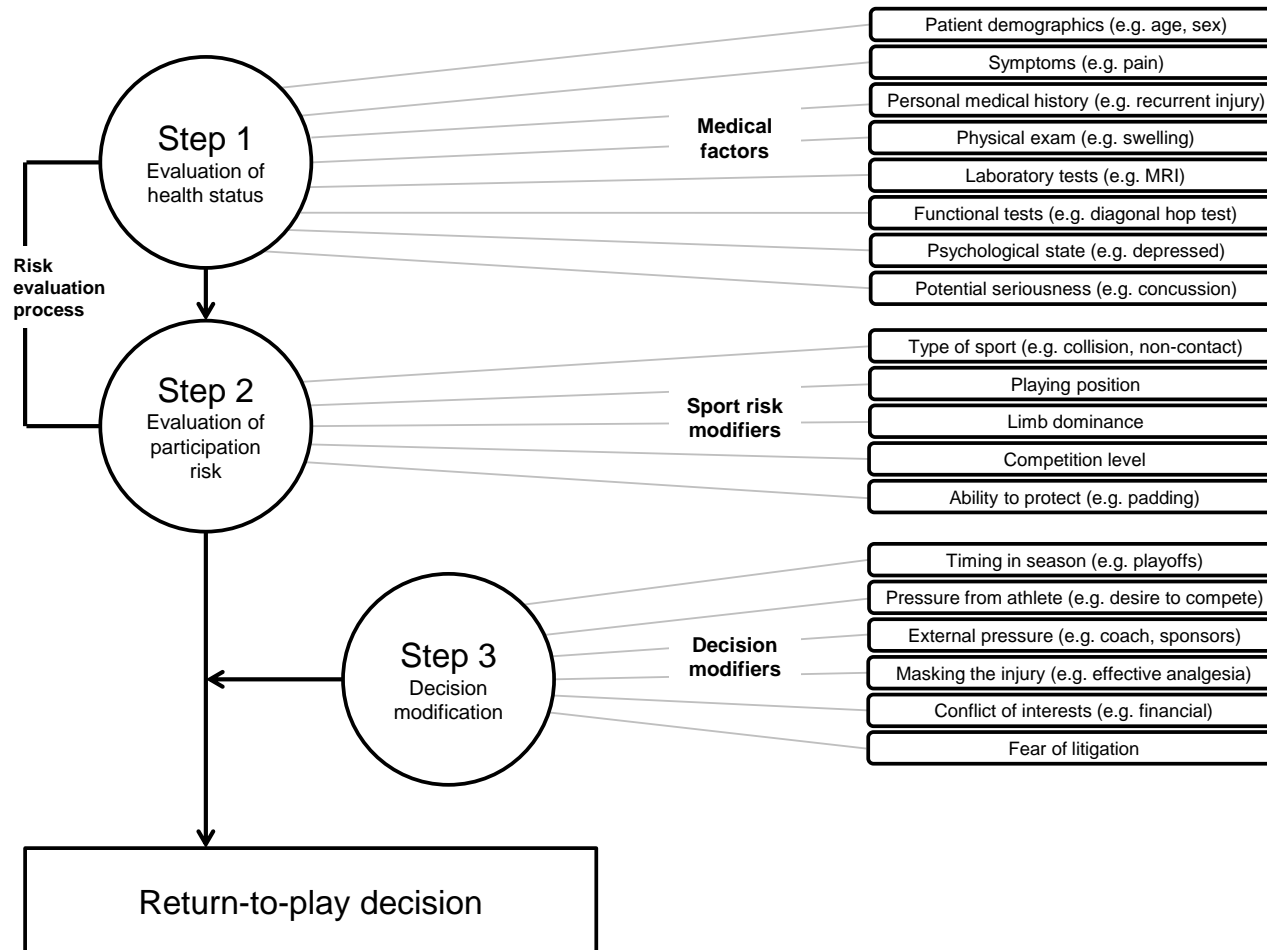


Figure 2.5 Decision-based return-to-play model (Creighton et al., 2010). This model describes the three-step process that clinicians are likely to follow (either consciously or subconsciously) when making return-to-play decisions for injured athletes.

2.6.7 *Injury burden*

It is argued that the injuries resulting in the greatest total absence from playing and training should be the primary concern for injury prevention strategies, and that these injuries may not necessarily be the most common or severe injuries (Brooks and Kemp, 2008). Indeed, in a study investigating the epidemiology of injuries in English professional Rugby Union, only one of the five most common (based on injury incidence rates) and severe (based on days absence) injuries appeared amongst the top five injuries with the greatest injury burden (Brooks et al., 2005a). Injury burden is a product of the probability that an injury will result from an activity (i.e. incidence rate) and the consequences of the injury (severity) (Brooks and Fuller, 2006) and may be used to quantify the overall risk of injury.

2.6.8 *Training and match exposure*

Typically, training exposure is several times higher than match exposure in a given period. As such, the two should be reported separately to allow the calculation of injury incidence rates for both, and prevent the true injury incidence rate from being masked (Brooks and Fuller, 2006). The rugby injury consensus statement defines match exposure as play between teams of different clubs (Fuller et al., 2007c). For instances in which clubs hold fully-refereed trial or selection matches between A and B teams, the two teams would be treated as though they were separate clubs, and the exposure recorded as match exposure. Training is defined as:

‘Any team-based or individual physical activities performed under the guidance of the team’s coaching or fitness staff, which are aimed at maintaining or improving players’ rugby skills or physical condition.’

2.6.9 *Subsequent injuries*

The term ‘subsequent injuries’ refers to all injuries that succeed an initial injury incurred by an individual (Hamilton et al., 2011a), and therefore incorporates both multiple and recurrent injuries. The consensus statement for injuries in Rugby Union (Fuller et al., 2007c) defines a recurrent injury as:

‘An injury of the same type and at the same site as an index injury and which occurs after a player’s return to full participation from the index injury.’

The statement then goes on to further classify recurrent injuries based on the time between a player's return to full participation and the occurrence of the re-injury: within 2 months is referred to as an 'early recurrence'; between 2 to 12 months is referred to as a 'late recurrence'; and more than 12 months is referred to as a 'delayed recurrence'. However, no studies to date have made use of these classifications in Rugby Union epidemiology investigations.

Fuller et al. (2007a) noted that these statements do not differentiate between the types of recurrent injuries that can occur. Given that a previous injury may influence the risk of sustaining a similar injury, and overall injury risk (Arnason et al., 2004b; Ullah et al., 2012), it may be necessary to further subcategorise recurrent injuries in order to understand the role of previous injury as a risk factor. Fuller et al. (2007a) proposed a recording framework that describes recurrent injuries as either 'exacerbations' or 'reinjuries' based on whether a player was fully recovered from the preceding index injury (as determined by medical opinion). A reinjury is a repeat episode of a fully recovered index injury, whilst an exacerbation is a worsening in the condition of an index injury from which the player was not fully recovered. The authors (Fuller et al., 2007a) believe this will help researchers investigate risk factors for these two types of recurrent injuries separately, and will also allow them to determine how well players have been rehabilitated before returning to full participation. To date, this concept is yet to be used in published studies using Rugby Union cohorts.

A further development in the classification of recurrent injuries was provided by Hamilton et al. (2011a), who recommended that injuries be coded as: (1) New injury = different location; (2) Local injury = same location but different type and (3) Recurrent injury = same location and same type. This 'Subsequent Injury Definition' process is outlined in Figure 2.6. The authors (Hamilton et al., 2011a) favoured the use of the term 'subsequent' injury to incorporate both multiple and recurrent injuries.

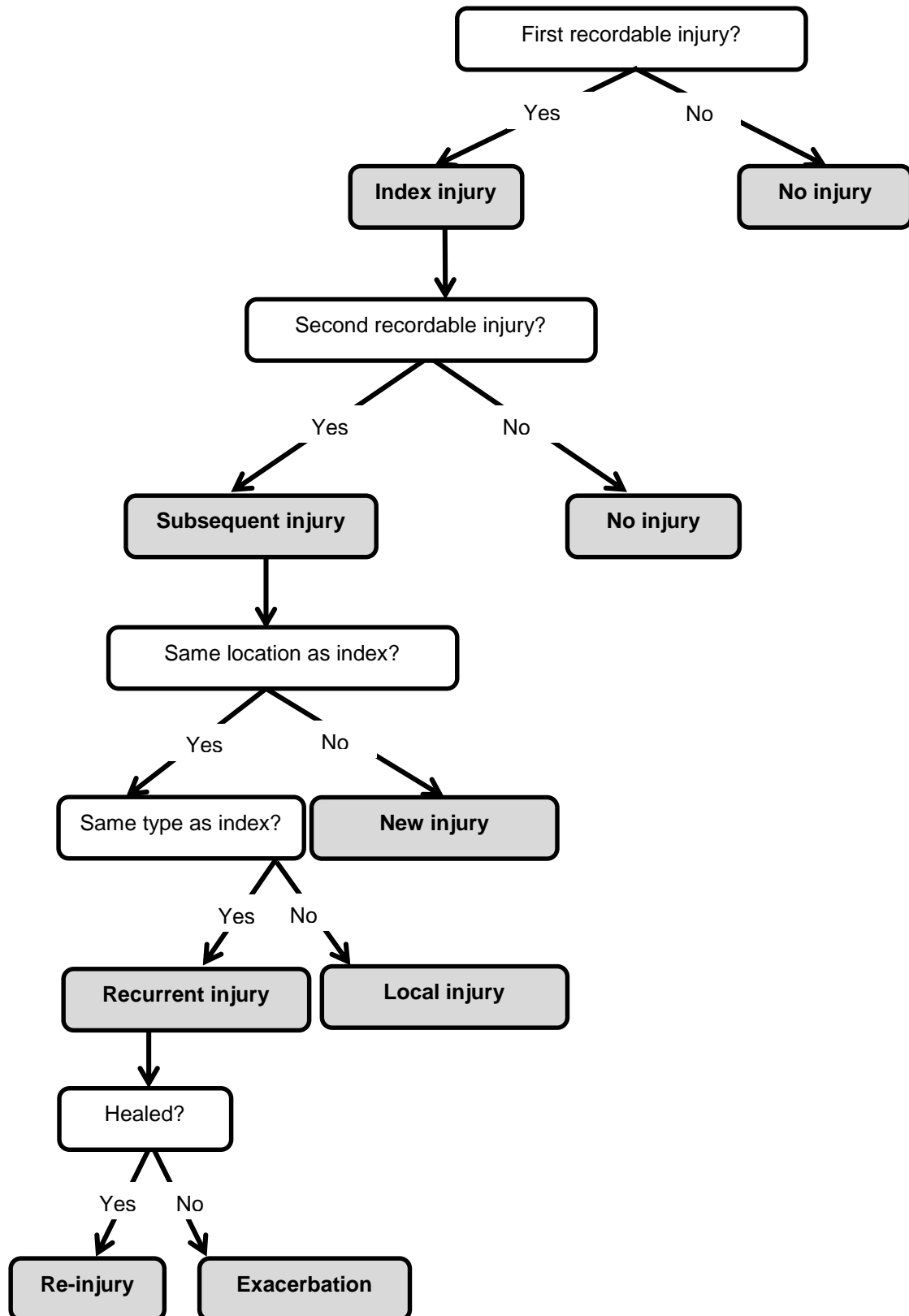


Figure 2.6 Subsequent Injury Definition process (Hamilton et al., 2011a). This process describes the classification of subsequent injuries as: New (different site); Local (same site and different type); or Recurrent (same site and type).

The most recent taxonomy of recurrent injuries, the Subsequent Injury Categorisation (SIC) model, aims to explore the extent to which injuries are directly related to previous index injuries in greater detail (Finch and Cook, 2013). Given that the nature/type of repeat injuries, as opposed to the general location of the injury (e.g. knee or ankle) alone, is also likely to be pertinent when classifying subsequent injuries (Fuller et al., 2007a), the SIC model includes ten dependency structures between injury types (Table 2.1). In addition, the SIC model highlighted the fact that it is inappropriate to use the first injury in a chronological sequence as the index for all subsequent injuries. The SIC model was applied to a community Australian Football injury dataset; 16% of all subsequent injuries were coded as being directly related to previous index injuries, compared with 12% when injuries were categorised using Hamilton et al.'s Subsequent Injury Definition scheme (Finch and Cook, 2013). However, Shrier and Steele (2013) advise that incorporating an *a priori* subjective assessment of whether an injury is related to a previous index injury (as necessitated within the SIC scheme) is likely to underestimate the total causal effect of the index injury, and would require the assessors to be blinded to the research question. As an example, Finch and Cook (2013) present a case where the index injury was a fully healed fractured leg that occurred due to a blow, whilst the subsequent injury was a second fracture after the index injury had fully healed. Finch and Cook (2013) classify this as an 'exact same injury in terms of body site and nature, not related to an index injury'. In contrast, Shrier and Steele (2013) highlight that the subsequent injury may have resulted from impaired proprioception due to the index injury, and, by using the Subsequent Injury Classification scheme the relationship between the two would not be identified because *a priori*, it had been decided that the two were not related. Moreover, the SIC scheme would require extensive clinical knowledge and may introduce substantial inter-club variation in reporting. For instance, when medical staff or players move clubs, knowledge of the intricate relationships between a given player's subsequent injuries is likely to be lost.

Table 2.1 Subsequent Injury Categorisation Model (Finch and Cook, 2013), which takes into account the need to include both acute and overuse injuries and ten different dependency structures between injury types

Subsequent injury characterised by body site and nature	Definition of Finch and Cook (2013)	Definition of Hamilton et al. (2011a) †	Definition of Fuller et al. (2007a) †
No Injury	None (1)	Not considered	Not considered
Exact same injury in terms of nature and body site	Acute onset which occurs after full recovery of index injury i—related to index injury i (2)	Recurrent	Reinjury
	Acute onset exacerbation or reinjury before full recovery—related to index injury i (3)		Exacerbation
	Continual or sporadic experiences of pain or other physical discomfort—related to index injury i (4)‡	Not clear	Not clear
	Continual or sporadic experiences of pain or other physical discomfort—not related to index injury i (5)‡		
Injury to same body site but different nature	Not related to index injury i (6)	Not considered	Not considered
	Occurrence related to index injury i (7)	Local—but possibility of different relationships to index injury not considered	New—but possibility of different relationships to index injury not considered
Injury to different body part (irrespective of nature)	Occurrence not related to index injury i (8)		
	Occurrence related to index injury i (9)	New—but possibility of different relationships to index injury not considered	New—but possibility of different relationships to index injury not considered
	Occurrence not related to index injury i (10)		

*It is possible for there to be more than one index in a given sequence of injuries and the term index injury i refers to the ith index injury. i=1, 2, etc.

†These categorisations do not explicitly recognise new (multiple) index injuries, but the concept can be easily incorporated.

‡Categories relating to overuse injuries with no acute onset of symptoms.

2.6.10 Injury classification systems

Injury classification systems are used within sports injury epidemiology to help classify injury diagnoses, so that data can be compared and analysed accurately (Rae and Orchard, 2007). A number of classification systems have been used within epidemiological research, including the International Classification of Disease (ICD) (World Health Organisation, 2010), Orchard Sports Injury Classification System (OSICS) (Orchard, 1995), Sport Medicine Diagnostic Coding System (SMDCS) (Meeuwisse and Wiley, 2007), and National Athletic Injury/Illness Reporting System (NAIRS) (Powell, 1988).

The OSICS system is the most commonly utilised classification system in Rugby Union injury research (e.g. Brooks et al., 2005a; Brooks et al., 2005b; Fuller et al., 2008; Fuller et al., 2012a). It was developed in 1992 for use in a study that examined injuries in football codes in Australia (Seward et al., 1993). Earlier versions of the OSICS used a 3-digit classification; the first letter defined the body location, the second letter described the pathology, and the third gave more detailed information regarding the pathology. Rae et al. (2005) compared the OSICS-8 system to ICD-10, and found the OSICS-8 to have a higher pairwise agreement between coders (57.2% versus 35.3%), and was on average 23.5 minutes quicker to complete a coding task. However, the overall level of agreement for both systems was lower than the 70% level purposed by Bensing (1983) as an acceptable degree of agreement. Consequently, the OSICS-10 system was developed with the aim of improving the level of interuser agreement, primarily through the development of a 4-character system that includes more diagnoses that are applicable to a sports medicine setting (Rae and Orchard, 2007). The OSICS-10 was found to be a more encompassing system than the OSICS-8, as all diagnoses (assessed by eight clinicians) could be assigned an appropriate code compared with 87% with the OSICS-8 system. The overall level of inter-rater reliability was still shown to be only moderate, with a Fleiss' Kappa (k) score of 0.56. The level of agreement for the top three tiers of classification (tiers are organised for progressive diagnostic specificity) were higher, with k values of 0.95 (tier one), 0.76 (tier two), and 0.69 (tier three).

An injury report form similar to that used by several studies in Rugby Union epidemiology research (e.g. Brooks et al., 2005a; Brooks et al., 2005b; Fuller et al., 2008; Fuller et al., 2012a) has been tested for both reliability and validity (McManus, 2000). Specifically, ten panel members viewed a series of videotaped injuries, three times each over a five week period. The form was also trialed by 40 people in situ whilst observing four matches. Inter-rater and intra-rater reliability was 98% for the videotaped injuries, and similarly, the inter-rater reliability agreement between the 40 trialists watching matches in situ was also 98%. Thus, the tool was deemed to be a valid and reliable measurement instrument for injuries in Rugby Union.

2.6.11 Summary

There are numerous issues to consider when conducting and presenting sports epidemiology research. Variations in research design and methods of analysis can produce conflicting conclusions. The publication of a consensus statement for studies in Rugby Union has allowed for greater methodological consistency across studies, with consistent and comparable results. Consistent methodology is vital for accurately establishing the magnitude of the injury problem in Rugby Union, monitoring trends in injury risk across time, and identifying and evaluating areas of intervention. The recording of subsequent injuries has received attention in the literature, with two methods proposed for categorising repeated injury events within individual athletes. Potential limitations associated with the subsequent injury classification scheme (Finch and Cook, 2013) were noted, leaving the Hamilton et al. (2011a) scheme as the most suitable framework for recording such injuries at present.

2.7 Statistical issues in sport injury data

Alongside issues relating to the design and reporting of epidemiological studies of sports injuries, the chosen method of statistical analysis of such data will also strongly influence the study conclusion. This section will therefore address issues pertinent to the statistical analysis of sport injury data.

2.7.1 Survival analysis

Survival analysis describes a collection of statistical methods for which the outcome variable of interest is the time until an event occurs. Whilst survival analysis

techniques are commonly used to model time to death, they may be used to model any outcome variable that describes the time to any particular event (Hougaard, 1995). Indeed, the statistical analysis of time-to-event data is important in fields such as epidemiology, medicine, biology, economics, and engineering. Certain data sets require special consideration via survival analysis, as opposed to classical statistical methods, for a number of reasons. Perhaps the key feature of survival analysis that differentiates it from classical statistical analyses is data censoring. The exact survival times of all participants are not always known; censored observations may arise when either the ‘endpoint’ (e.g. injury) has not occurred by the time the data is to be analysed, or when the subject is lost to follow-up (e.g. leaves a club or retires). A censored observation contains partial information about the variable of interest, and these observations must be accommodated correctly to provide accurate estimates of survival times (Kaplan and Meier, 1958). Secondly, data of this form is typically highly skewed and therefore requires special consideration (Haertung, 2011). Other statistical methods, such as logistic regression, ignore survival times and censoring. As such, survival models are preferred for the analysis of these types of data.

The Cox proportional hazards model (Cox PH) is a commonly used survival model that is used to estimate survival probability after adjusting for both baseline hazard and predictor variables (Cox, 1972). The formula for the Cox PH is:

$$h(t, \mathbf{X}) = h_0(t) \exp \left[\sum_{i=1}^p \beta_i X_i + \dots + \beta_n X_n \right] \quad \text{Eq. 2.1}$$

Where \mathbf{X} represents a collection of predictor variables that is being modelled to predict an individual’s hazard. The hazard (h) at time t is the product of the baseline hazard, $h_0(t)$, and an exponential expression (e) to the linear sum of $(\beta_1, \dots, \beta_n)$, where the sum is over the p explanatory X variables (Kleinbaum and Klein, 1996). The hazard ratio (\widehat{HR}), which describes the hazard for one individual divided by the hazard for a different individual (with altered values for the set of predictors), is given by:

$$\widehat{HR} = \exp \left[\sum_{i=1}^p \beta_i (X_i^* - X_i) \right] \quad \text{Eq. 2.2}$$

The parameters of the Cox PH model are estimated using maximum likelihood, whereby the natural log of a likelihood function (describing the joint probability of obtaining the observed data as a function of the unknown parameters $[\beta's]$), is maximised. This is achieved by setting the partial derivative of the natural log of the likelihood function to zero, and then iteratively solving a system of 'score equations' (Kleinbaum and Klein, 1996). The Cox PH is robust to many data distributions and allows an estimate of the hazard ratio to be calculated without a requirement to know the baseline hazard. However, extensions of the Cox PH model must be used when time-dependent covariates are being investigated. Moreover, for outcome events that may occur more than once over a follow-up period (i.e. recurrent events), consideration must be given to the likely correlation among outcomes from the same individual.

A simple extension of the Cox proportional hazards model is the Andersen-Gill model, in which players continue to contribute to the risk set throughout the whole period of observation (Andersen and Gill, 1982). A limitation of this model is that it requires several substantial statistical assumptions, including that injuries are independent of one another. The Wei-Lin-Weissfeld total time model uses a marginal approach, whereby the effects of covariates on the hazards of individual events (the margins) are modelled with acknowledgement of the fact that observed event times are correlated, but without necessarily modelling this correlation (Wei et al., 1989). While this approach is suitable when considering the population average effect of risk factors on time-to-injury, it is not possible to investigate multivariate relationships among failure times (Haertung, 2011). The Prentice-Williams-Peterson gap time model is a conditional model that uses the duration since previous injury as the risk interval (Prentice et al., 1981). Injury events are stratified, so that different injury events can have different baseline hazards. However, the within-person correlation due to injury dependence is not captured.

The frailty model is a parametric approach for analysing recurrent event data that is likely to be correlated within individuals' repeated events (Kleinbaum and Klein, 1996). In epidemiological studies, it is impossible to include data pertaining to all risk factors, either because they unknown, or because they are difficult to measure

given time and financial constraints (Haertung, 2011). The omission of covariates leads to unobserved heterogeneity, and so a given population consists of individuals with different levels of risk that cannot be adjusted for (Haertung, 2011). Making estimates of hazard rates without accounting for heterogeneity caused by unmeasured covariates, and under the assumption that all individuals have the same risk of injury, will produce misleading results, namely underestimated hazards to an increasingly greater effect over time (Hougaard, 1991). The model used to estimate the hazard function using the frailty model is:

$$h_i(t) = h_0(t)e^{X_i\beta + \omega_i} \quad \text{Eq. 2.3}$$

Where the ‘frailty’ term, ω_i , is included to account for variability due to unobserved participant-specific factors, which can be a source of within-participant correlation (Vaupel et al., 1979). Thus, observations are clustered by participant, and each cluster (i.e. participant) shares the same level of frailty. The frailty term is a multiplicative random effect that acts on the baseline hazard function, and is typically assumed to follow a gamma distribution of mean 1 and variance θ , which is to be estimated. The estimated hazard ratio from the frailty model may be interpreted in two ways; one is as a comparison of two individuals with the same level of ‘frailty’ (whilst controlling for other measured covariates), and the second is by comparing the individual with themselves (Kleinbaum and Klein, 1996). That is, the hazard ratio describes the effect on an individual’s hazard per one unit increase in the risk factor (for continuous variables) or in the presence of a factor (for categorical variables).

There are four types of frailty models, to account for various forms of survival data. The simplest form is the shared frailty model (Rondeau et al., 2003), which is appropriate for instances when observations are clustered into groups (e.g. players with varying levels of underlying injury risk). A nested frailty model accounts for hierarchical clustering of data (e.g. players within clubs) by including two nested random effects terms (Rondeau et al., 2006). A joint frailty model may be applicable to medical settings in which relapses (recurrent events) are likely to increase the risk of death (terminal events) (Rondeau et al., 2007). This form of frailty model fits two hazard functions to the recurrent and terminal events jointly. The additive frailty model is suitable for meta-analyses of clinical trials, as it

includes two correlated random effects at the trial level that act multiplicatively on the hazard function and on the interaction with treatment (Rondeau et al., 2008). In addition, the conditional frailty model has been recommended as a robust strategy for estimating effects in repeated events survival models where both heterogeneity across individuals and event dependence are present, which is likely to be rule, rather than the exception, in the study of recurrent events (Box-Steffensmeier and De Boef, 2006). Event dependence refers to cases where the occurrence of one event may make further events more or less likely to occur (e.g. an injury may increase the likelihood of a subsequent injury). The conditional frailty model combines a random effect (to account for unobserved heterogeneity across individuals) with gap time formulation of the risk set (to incorporate event dependence), and has been shown to be robust to both of these conditions (Box-Steffensmeier and De Boef, 2006).

The use of survival models for the analysis of sport injury data is currently in its infancy. Waldén et al. (2012) used a robust Cox PH model to assess the efficacy of a neuromuscular warm-up intervention aimed at reducing the incidence rate of acute knee injuries. Similarly, Nordstrom et al. (2014) used a Cox PH model to compare the risk of sustaining a subsequent injury in participants with and without a previous concussion injury. Frailty models have been used extensively in medical contexts to analyse survival data, but have only recently been applied to recurrent sport injury data. The frailty model has been identified as the best-suited method for analysing recurrent sport injury data in comparison with the Cox PH model and its extensions (Ullah et al., 2012). Using a cohort of professional rugby league players, Gabbett et al. (2012a) applied a frailty model to identify risk factors for contact injuries; players with poorly developed prolonged high-intensity intermittent running ability and upper-body strength were found to have a higher incidence rate of contact injuries. Using a similar cohort, Gabbett et al. (2012b) also used a frailty model to investigate skill qualities as risk factors for contact injury. Interestingly, players with longer decision times had a lower risk of injury, which the authors attributed to the fact that these players may inadvertently avoid the heavy collisions that cause injury. These studies demonstrated the applicability and usefulness of survival models for analysing sport injury data, and in particular the frailty model for

analysing recurrent sport injury data and identifying risk factors for injury. To date, the frailty model has not been applied to elite Rugby Union injury data.

2.7.2 *Machine learning*

Breiman (2001b) describes ‘data’ as being generated by a black box, in which a vector of input variables (x) enter one side, and response variables exit on the other side. Within the black box, nature functions to associate the input and response variables. The aim of all researchers when analysing data is to understand the association between the input and response variables, and/or be able to predict future responses based on inputted data. There are two broad approaches to answering such questions: the traditional data modelling approach, whereby a model linking the independent and dependent variables is assumed (e.g. logistic regression, Cox PH model), and the parameters of this model are estimated from the data, and the algorithmic modelling approach, which involves finding a function (or algorithm) that acts on independent variables to predict the responses (e.g. decision tress, neural nets). These approaches are represented in Figure 2.7. The algorithmic approach is far less common, but may hold greater utility for answering research questions (Breiman, 2001b). Namely, relatively simple parametric models undertaken within the traditional data modelling approach are unlikely to fully describe data generated by complex systems. In many cases, algorithmic models can provide a greater degree of accuracy, and a better understanding of the underlying mechanisms, than traditional data modelling approaches. Indeed, Breiman (2001b) reported a reduction in predictive error rate of almost 30% when using an algorithmic approach (random forests) to assess variable importance in a survival data set, when compared with a traditional data modelling approach (logistic regression). The complex and multi-factorial nature of sport makes algorithmic modelling approaches a suitable method for predictive tasks. Indeed, algorithmic modelling approaches have recently been used within various sports settings to answer questions relating to performance enhancement (Joseph et al., 2006; Ofoghi et al., 2013; Unold, 2011) and injuries (Kampakis, 2013), but are yet to be utilised in Rugby Union.

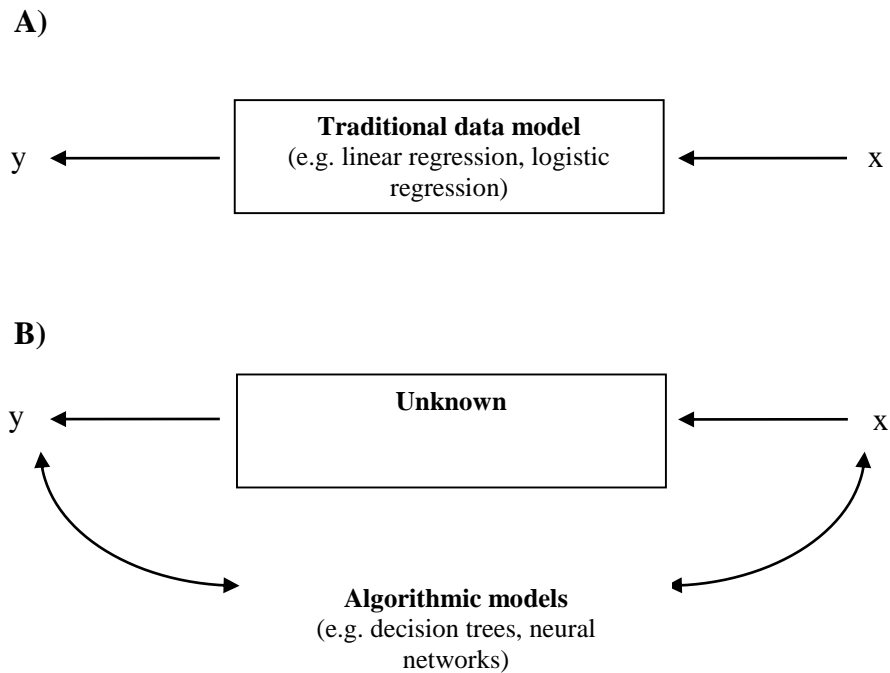


Figure 2.7 Representation of the A) the traditional data modelling approach and B) the algorithmic modelling approach, which both attempt to describe the ‘black box’ of nature (Breiman, 2001b).

Predictive modelling describes the process by which a mathematical tool or model is created to try to best predict the probability of an outcome (Geisser, 1993). There are several key elements to the model building process, which will be outlined briefly below and are summarised from Kuhn and Johnson (2013).

2.7.2.1 Data pre-processing

Data pre-processing techniques typically relate to the transformation, addition or deletion of variables from a data set, and can be critical to the predictive ability of the resultant model. The requirement for such techniques is dependent on the predictive model being used. For instance, tree-based models are commonly insensitive to the nature of the predictor variables, whilst linear regression models are not. Examples of data pre-processing techniques include centering and scaling, transformations to resolve skewness (e.g. log transformation), transformations to resolve outliers (e.g. spatial sign), data reduction (e.g. Principle Component Analysis), removing predictors (e.g. those that show substantial collinearity), and adding predictors (e.g. quadratic terms).

2.7.2.2 *Data splitting*

Ideally, a model should be evaluated using samples that were not used to build or tune the predictive model. To accomplish this, a proportion of data (typically 10-30%) may be set aside to evaluate the final model and is referred to as the ‘test’ or ‘validation’ data set, whilst the samples used to create the model are referred to as the ‘training’ data set. When sample size is not sufficiently large, resampling methods (e.g. cross-validation) may instead be used to evaluate model performance using the training data set.

2.7.2.3 *Model selection*

There are numerous models available for predictive modelling, which are summarised in Table 2.2. Model choice will firstly depend on the nature of the outcome variable (i.e., numeric or categorical). Thereafter, a variety of modelling techniques should be employed and evaluated using variables such as the root mean squared error and R^2 values (for regression models) or Youden’s J Index and Receiver Operating Characteristics (for classification models) to select the most appropriate model. Visualisations of the model fit are also encouraged.

Table 2.2 Summary of machine learning models and their key characteristics (Kuhn and Johnson, 2013)

Model	Allows $n < p$	Pre-processing	Interpretable	Automatic feature selection	# Tuning parameters	Robust to predictor noise
Linear regression [†]	<i>X</i>	CS, NZV, Corr	✓	<i>X</i>	0	<i>X</i>
Partial least squares	✓	CS	✓	0	1	<i>X</i>
Ridge regression	<i>X</i>	CS, NZV	✓	<i>X</i>	1	<i>X</i>
Elastic net/lasso	<i>X</i>	CS, NZV	✓	✓	1-2	<i>X</i>
Neural networks	✓	CS, NZV, Corr	<i>X</i>	<i>X</i>	2	<i>X</i>
Support vector machines	✓	CS	<i>X</i>	<i>X</i>	1-3	<i>X</i>
MARS/FDA	✓		0	✓	1-2	0
K-nearest neighbours	✓	CS, NZV	<i>X</i>	<i>X</i>	1	0
Single trees	✓		0	✓	1	✓
Model trees/rules [†]	✓		0	✓	1-2	✓
Bagged trees	✓		<i>X</i>	✓	0	✓
Random forest	✓		<i>X</i>	0	0-1	✓
Boosted trees	✓		<i>X</i>	✓	3	✓
Cubist [†]	✓		<i>X</i>	0	2	✓
Logistic regression*	<i>X</i>	CS, NZV, Corr	✓	<i>X</i>	0	<i>X</i>
[LQRM]DA*	<i>X</i>	NZV	0	<i>X</i>	0-2	<i>X</i>
Nearest shrunken centroids*	✓	NZV	0	✓	1	<i>X</i>
Naïve Bayes*	✓	NZV	<i>X</i>	<i>X</i>	0-1	0
C5.0*	✓		0	✓	0-3	✓

[†] Regression only * Classification only ✓ Yes *X* No 0 In some cases
 CS = Centering and scaling NZV = Identify 'near-zero variance' predictors

Corr = Identifying correlated predictors

2.7.3 *Sample size*

The sensitivity of a study, or its statistical power, describes the probability of rejecting a false null hypothesis (i.e. not committing a Type II error). The statistical power achieved by studies investigating risk factors for sports injuries is dependent upon the size of the effect being investigated, the acceptable level of significance and the sample size; increasing the sample size is the only viable option for increasing statistical power in epidemiological studies as the significance level is typically set before the study is conducted, and the effect size is determined by the difference in the prevalence of injury between the investigated groups (i.e. those with and without the risk factor) (Bahr and Holme, 2003). Brooks and Fuller (2006) illustrated the effect that increasing the number of clubs in a Rugby Union injury study had on the confidence intervals for the effect statistic; when the sample population was increased from nine to twelve clubs, the incidence rate of thigh match injuries in forwards and backs changed from being unclear to statistically different. However, researchers in this field are typically limited to the use of convenience sampling. Moreover, in many cases the sample will already represent the whole available population, for example in injury surveillance studies at Rugby World Cup tournaments (e.g. Fuller et al., 2012a), and so it is not possible to increase the sample size further. In such cases, any inferences made should be treated with appropriate caution, given that there may not be sufficient statistical power to detect true differences in the value of the effect statistic (Hopkins, 2006a).

2.7.4 *Magnitude-based inference*

The traditional approach to inferential statistics is null-hypothesis testing, in which a *P*-value is produced from an outcome statistic; the *P*-value is the probability of obtaining any value larger than the observed effect if the null hypothesis were true (Biau et al., 2010). This approach may not be appropriate, as the null hypothesis of ‘no difference’ is always false – there are no truly ‘zero’ effects in nature, and a researcher will usually have good reason to believe the effect will be different from zero (Batterham and Hopkins, 2006). The important issue is not whether an effect is present, but the magnitude of the effect and whether it would make a worthwhile difference to an athlete or team. Unfortunately, the *P*-value alone provides no indication of such factors (Hopkins et al., 2009b). An outcome statistic with $p < 0.05$ could easily represent an effect that is practically irrelevant to an athlete or team,

while a non-significant result could in fact be useful, but a combination of small sample size and measurement variability may have pushed the effect beyond the '0.05' threshold (Batterham and Hopkins, 2006). As Rosnow and Rosenthal (1989, p.1277) suggested, "Surely God loves the 0.06 nearly as much as 0.05?" A more practical approach is to express uncertainty in the true value as confidence limits, which define the likely range of the true value. It is then possible to evaluate the real-world significance of this uncertainty by assessing where this range lies in relation to values that are substantial in a beneficial or harmful sense (Hopkins, 2010). Quantitative likelihoods that the true value is beneficial, trivial and harmful can then be given to guide a decision about the utility of the outcome (Batterham and Hopkins, 2006).

Recently, a review of the magnitude-based inference approach has outlined a number of potential limitations with this method (Welsh and Knight, 2014). Welsh and Knight (2014) imply that the magnitude-based inference approach ignores data structure, multiple covariates, distribution and scale of the outcome variable, and presentation of effect size, although all of these issues have been addressed in the various publications accompanying the magnitude-based inference approach (Batterham and Hopkins, 2006; Hopkins et al., 2009a; Hopkins, 2007; Hopkins, 2010). Moreover, the authors claim that the magnitude-based inference approach is just another form of null-hypothesis significance testing but, in reply, Batterham and Hopkins assert that it is philosophically and statistically distinct. The magnitude-based inference approach requires researchers to define practically meaningful values of an effect, and then provides a framework for interpreting the level of uncertainty in the effect with reference to these values; this makes it an attractive approach for many sports-related research questions. Issues were also raised regarding the probability of making a Type I error when using the magnitude-based inference approach, which was described as being 10 times higher than the standard value of 0.05. Yet, Batterham and Hopkins state in their reply that using analytical formulae and simulation, they have verified that the Type I error rate (false discoveries of clear substantial effects, when true effect is null) is in fact much smaller than stated by Walsh and Knight, and is acceptable given that probabilistic terms representing the level of evidence (e.g. "possibly beneficial") accompany the "errors". For instance, rates for *likely*, *very likely* and *most likely*

substantial effects were 14%, 1.6% and 0.1%, respectively. Overall, the magnitude-based inference approach may be viewed as a hybrid of frequentist and Bayesian methods, and is becoming increasingly popular as a means of overcoming the problems associated with null-hypothesis significance testing (Cohen, 1994).

2.7.5 *Summary*

This section addressed the key statistical issues relating to epidemiological studies of sports injuries. Survival models, and in particular random effects survival models (frailty models), have been identified as an appropriate means by which to comprehensively analyse sport injury data. In particular, these models accommodate censored observations and highly skewed data, and describe the impact of included explanatory variables on the likelihood of injury. Many traditional statistical models necessitate that all observations are independent of one another; this assumption is likely to be violated in studies that include repeated observations across players. Multilevel modelling techniques are therefore required to ensure accurate inferences are made from such data. Related to this, inferences based solely on *P*-values do not adequately convey information regarding the practical impact of the effects. Methods that assess where the likely range of the effect (i.e. the confidence interval) lies in relation to values that are substantial in a beneficial or harmful sense may be preferable. Elsewhere, the complex and multi-factorial nature of sport injury data make algorithmic modelling approaches a viable option for answering research questions. Yet, all of the statistical approaches outlined above (i.e. survival analyses, multilevel modelling, magnitude-based inferences and algorithmic modelling) have received limited attention in sports injury literature, and are yet to be considered in any epidemiological studies involving elite Rugby Union players.

2.8 Risk factors for injury in collision sports

Injury risk factors describe any variable that may influence an individual's risk of becoming injured. They are traditionally divided into internal (intrinsic) athlete-related factors, and environmental (extrinsic) factors, as outlined in Figure 2.4. This section will provide an overview of risk factors that have been identified in collision sport athletes. Intrinsic factors will be addressed first, followed by extrinsic factors.

Intrinsic risk factors

2.8.1 Age

Although non-modifiable, age may be an easily identifiable risk factor with which injury prevention strategies can be shaped. In English professional rugby, there has been a trend towards a younger average age over the past ten seasons, although this was only a significant result for prop forwards (Fuller et al., 2012b). Older age has been identified as a risk factor for injury in amateur Rugby Union players (Quarrie, 2001), as well as in other populations such as soccer players (Lindenfeld et al., 1994) and military recruits (Knapik et al., 2001). An increased injury risk with older age may be explained via the cumulative load theory (Section 2.4.3), which states that mechanical degradation associated with repeated and prolonged usage may reduce the stress-bearing capacity of tissue (Kumar, 2001). Moreover, physical characteristics (e.g. body mass, strength and speed) may differ between older and younger players, which may be associated with greater collision forces (Norton et al., 1999). However, many of the findings relating to age may also be confounded by playing level. Indeed, age was not a significant risk factor for injury within amateur Rugby Union players when an adjustment for grade of match was made (Quarrie, 2001). In the only study to date to assess the influence of age as an injury risk factor in professional Rugby Union players, the youngest players (<21 years old) were reported to have an increased risk of injury compared with older players, with the risk being higher in the youngest backs compared with the youngest forwards (Brooks, 2004). Thus, exposure to senior professional Rugby Union at a young age may be a risk factor for injury, possibly due to such players not yet developing the physical characteristics required to enable them to withstand the demands of Rugby Union at this level. This may be especially pertinent, given the trends towards a younger average age in English professional rugby over the past ten seasons (Fuller et al., 2012b).

Age may have varying effects across different types of injuries. For instance, in Australian football, increases in age were linked to a greater risk of muscle strain injuries (Orchard, 2001), lower limb injuries (Seward and Orchard, 2004), and hamstring muscle strain injuries (Verrall et al., 2001), possibly as a consequence of age-related degenerations. Conversely, the risk of head/neck and nervous system

injuries in professional Rugby Union players was lowest in the oldest age group (>29 years) (Brooks, 2004). It may be that greater playing experience allows these players to more effectively avoid situations that incite such injuries, or it could be indicative of an underreporting of head/neck and neural injuries in younger players (Targett, 1998). Overall, studies investigating the influence of age as a risk factor for injury in Rugby Union have been sparse. Age may modulate the risk of specific injury types in a divergent manner, and so more detailed investigations are required before injury prevention strategies can be guided appropriately.

When considering the influence of age as an injury risk factor, the potential impact of 'survivor bias' must also be recognised (Rothman et al., 2008). That is, frail individuals are more likely to be removed from the population before they reach the older age categories, whilst those individuals who continue to play elite Rugby Union for extended periods (i.e. past the age of 30) are likely to possess some other characteristic that enables them to survive. As such, survivor bias may be thought of as a special case of selection bias, and can have the effect of biasing the estimate of age as a risk factor away from the null.

2.8.2 *Training volume and load*

Conditioning and skills training programmes are used to improve the performance of athletes, and ensure they are able to meet the physical and technical demands of their sport (Gamble, 2004; Hoffman and Kang, 2003). Thus, training is a critical part of an elite athlete's regimen for success. The principle of training can be simplified to a dose response relationship, whereby a 'dose' of training results in a measureable 'response' to a physiological or performance measure (Rhea et al., 2003). The Banister impulse-response model quantitatively relates an athlete's performance ability at a given time to the cumulative effect of prior training loads (Calvert et al., 1976). Daily training loads are postulated to have both a positive training effect on fitness and a negative training effect on fatigue, with predicted performance being calculated as the difference between the two. The model includes parameters to describe the time-course of the positive and negative training effects, which can be optimised to closely describe actual performance data. The impulse-response model can subsequently be used to facilitate enhanced performance through simulations and influence curves (Clarke and Skiba, 2013).

The potential improvements in performance that an increased training load may produce must be balanced with the potential for increased risk of injury to players (Gamble, 2004). A mismatch between physical and psychosocial stress and recovery may result in local overload (injuries) or general overload (illnesses) (Brink, 2010).

Numerous methods have been used to quantify training load, including heart rate measurements, questionnaires and diaries, global positioning systems (GPS) and session rating of perceived exertion (sRPE). Given the varying modalities of training used in elite Rugby Union, a limitation of heart rate and GPS-based measures is their inability to effectively capture non-aerobic modes of exercise (e.g. resistance training) (Borresen and Lambert, 2009). Foster et al. (1996) introduced the sRPE measure in order to simplify the measurement of training load across multiple training modalities. Typically, athletes will be asked to provide a rating of the overall difficulty of a given session 30 minutes after its completion. This value is then multiplied by the duration of the session in minutes, to give a 'load' in arbitrary units [AU]. For resistance exercise, sRPE is multiplied by the number of repetitions performed. However, Sweet et al. (2004) reported that sRPE for resistance training is influenced more by load than by volume, such that performing fewer repetitions with a heavier load is perceived to be harder than performing more repetitions with a lighter load (despite total workload possibly being smaller). Nonetheless, strong correlations between both heart rate and sRPE ($r = 0.65-0.95$) and blood lactate responses and sRPE ($r = 0.86$) have been reported in collision-based team sports settings (Clarke et al., 2013; Gabbett and Domrow, 2007), suggesting that sRPE is a valid tool for quantifying training load in collision sports. Moreover, the same authors reported an intra-class correlation coefficient for this measure of 0.99 (measured in a subset of 11 players that completed two identical sessions one week apart), suggesting the RPE scale is also a reliable measure of session difficulty. Indeed, the product of sRPE and session duration is the most commonly used method for quantifying training loads in extant literature relating to collision sports (Gabbett and Domrow, 2007; Gabbett and Jenkins, 2011; Killen et al., 2010; Piggott, 2008; Rogalski et al., 2013).

Using a cohort of 502 professional Rugby Union players, Brooks et al. (2008) reported that higher training volumes (>9.1 h per week) did not increase the incidence rate of injuries, but did increase the severity of match injuries (particularly those sustained during the second half). Fitness testing, defence and rucking and mauling were found to be the training activities that carried the highest injury risk. A training volume of between 6.1 and 9.1 h per week resulted in the lowest risk of injuries, and so was considered 'optimal' for this cohort. However, this study did not include a measure of the intensity of training sessions, which is likely to influence overall fatigue and thus injury risk.

The relationship between training load and injury has been investigated by several authors, although no studies have been conducted using Rugby Union cohorts. In professional rugby league players, training load (calculated by multiplying sRPE by the duration of the session) was significantly related to overall injury rates ($r = 0.82$) (Gabbett and Jenkins, 2011). In addition, larger one-week, two-week and previous to current week changes in training load were all significantly related to a higher injury risk in Australian footballers (Rogalski et al., 2013), whilst three-week cumulative loads derived from GPS measurements were also found to be associated with increased risk of injury in this population (Colby et al., 2014). These findings indicate that both the pattern of change and cumulative effect of training loads may be associated with injury risk, in addition to the absolute weekly or daily training load value. More recently, evidence of an inverted-U relationship between training load and stress markers has been reported in elite female futsal players (Milanez et al., 2013), whereby daily training load values outside of an optimal range (~ 343 - 419 AU) were associated with an increase in stress symptoms. Gabbett (2010) investigated the relationship between training loads, training phase and injury risk in elite Rugby League players (Figure 2.8). Subsequently, Gabbett (2010) developed an injury prediction model for non-contact, soft-tissue injuries in elite rugby league players. The model had a positive prediction value of 62%, with players that exceeded their planned training threshold values found to be 70 times more likely to suffer a non-contact, soft-tissue injury. Thus, the injury prediction model may provide greater sensitivity in the prescription of training loads than the intuition and 'gut feel' of conditioning staff alone, and so may be useful for the prevention of such injuries.

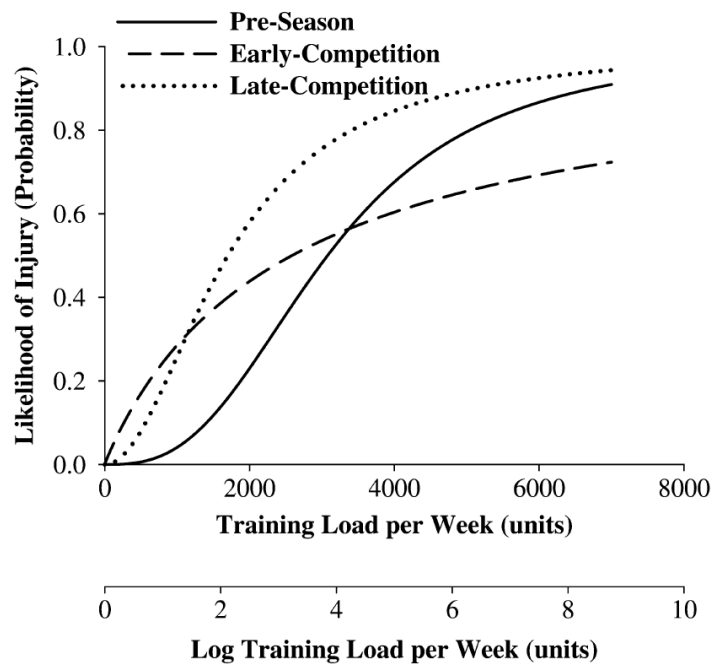


Figure 2.8 Relationship between training load, training phase and likelihood of injury in elite collision sport athletes (Gabbett, 2010).

In addition to the relationship between training load and injury risk, Foster (1998) suggested that training monotony (daily training load/standard deviation, calculated over a period of one week) and training strain (the product of training monotony and weekly load) may be predictors of undesired training outcomes. Indeed, there is some evidence to suggest that so long as heavy training is remittent and interspersed with ‘easy’ days, then negative training outcomes are less likely to occur (Bruin et al., 1994; Foster, 1998). However, studies investigating the relationship between these training indices and injury risk in team sport athletes are sparse. Piggott (2008) found no strong correlations between training monotony and either injury or illness in a cohort of 16 Australian Football League athletes, although the very limited sample size and follow-up period (15 weeks) used in this investigation likely negated the true relationship from being determined. In female collegiate soccer players, preceding spikes in strain and monotony were found to be predictors of illness (Putlur et al., 2004), although the relationship of these factors with injuries was not determined. In elite youth soccer players, physical stress (training duration, training load, monotony and strain) over the preceding week were all related to acute injuries, but not to overuse injuries (Brink et al., 2010). These findings suggest that separate analyses for acute and overuse injuries are required, as they

appear to have differing risk factors. Milanez et al. (2013) reported that in elite female futsal players, weekly training strain values of above ~3060 AU were associated with an increase in stress symptoms and a decrease in salivary secretory immunoglobulin A levels. Further research on these indices (training strain and monotony) is required to elucidate their role as risk factors for injury.

Additional training load variables that have received little attention in the literature include an exponentially weighted moving average variable and a 'training-stress balance' variable. The exponentially weighted moving average describes the cumulative load a player has been subjected to and is calculated using a decay factor (f) with a value between 0 and 1, using the following formula (Eq. 2.4):

$$\text{Exponentially weighted moving average} = f \times (y_t) + (1 - f) \times S_t \quad \text{Eq. 2.4}$$

Where y_t is the previous day's training load value, and S_t is the most recent exponentially weighted moving average value. The resultant load value is effectively a time weighted moving average, whereby a higher value of f discounts older observations at a greater rate (Holt, 2004). An exponentially weighted moving average with an f value of 0.1 was found to be associated with injury risk in a professional Rugby Union team, with high values associated with reduced non-contact injury risk (possibly due to the protective effects of high fitness levels), but increased match contact injury risk (Kara, 2013). However, this work is yet to be published in a peer-reviewed journal, and the exponentially weighted moving average variable has not been investigated in any other cohorts.

The training-stress balance variable is calculated by dividing a player's acute workload (one-week load) by their chronic workload (four-week rolling average). Acute and chronic workloads were intended to represent 'fatigue' and 'fitness', respectively, as per the Banister impulse-response model (Calvert et al., 1976). Training-stress balance values above 200% were shown to substantially increase subsequent injury risk in elite cricket fast bowlers (Hulin et al., 2014), but this variable remains to be explored within other sporting populations.

2.8.3 *Match loads*

There appears to be a growing concern over the demands being placed on professional Rugby Union players with regards to the number of matches they are expected to play (James, 2014b; James, 2014a). Qualitative investigations have attributed factors such as heavy playing loads, limited recovery time in the off-season, and an ‘anti-rest culture’ as causes for burnout syndrome and increased injury incidence rates in Rugby Union players (Cresswell and Eklund, 2006). However, no quantitative data exist to support these findings. In professional football, a correlation between match exposure of European players before the 2002 World Cup and their injuries and performance during that World Cup was reported (Ekstrand et al., 2004a). Additionally, congested fixture periods have been associated with increased injury risk in the ensuing period (Dellal et al., 2013; Dupont et al., 2010). In semi-professional rugby league players, changes in match load (calculated by multiplying the match intensity by the time each player participated in the match) were positively and significantly correlated with changes in the incidence rate of match injuries (Gabbett, 2004). Together, these findings suggest that a higher number of matches played in the period proximal to a given match may increase injury risk, but this is yet to be investigated in Rugby Union. Overall, the temporal effect of match loads on injury risk in elite Rugby Union players is yet to be examined appropriately.

2.8.4 *Previous injury*

Previous injury is often proposed as a risk factor for subsequent injury, but most studies rely on players reporting their own reported medical history and so have a high potential for recall bias. An injury may modify a player’s intrinsic risk factors, and so change the player’s predisposition to injury (Meeuwisse et al., 2007). Consequently, the player may be exposed to the same, or different, extrinsic risk factors (e.g. a hard pitch surface) and have a different susceptibility to injury (Meeuwisse et al., 2007). Indeed, there is evidence to suggest that previous injury episodes (of either the same or different type) can influence subsequent injury risk (de Visser et al., 2012; Häggglund et al., 2006; Orchard, 2001; Swenson et al., 2009). Orchard (2001), for instance, reported that a history of lower-limb muscle strain increased the risk of incurring future strains in other lower-limb muscles amongst players in the Australian Football League, and suggested that altered biomechanics

may explain this finding. However, studies utilising Rugby Union populations are sparse, and there is likely to be bias in analyses that do not account for individual predispositions toward injury. Indeed, Hamilton et al. (2011b) used a matched subset-analysis to compare injury risk *within* an individual (circus artists), and demonstrated that previous injury is not associated with an increased risk of subsequent injury for a given individual. The conditional matched-analysis, which compared time to first, second and third injuries amongst individuals with 3 or more injuries, showed that time to injury was similar for the first and all subsequent injuries: that is, an injury did not increase subsequent injury risk. Instead, previous injury was a marker for other traits (e.g. poor technique) that caused an individual to have a greater injury risk (“noncausal marker” theory; Hamilton et al., 2007). Typical analyses of previous injury as a risk factor compare the injury risk within an entire group with the injury risk *after* removing individuals with a certain predisposition to injury, and are therefore biased away from the null (Hamilton et al., 2011b). That said, while the cohort used in this study (circus artists) appeared to return to their ‘baseline’ injury risk after recovering from an injury, this may not be the case in other athletic populations (e.g. those in which appropriate injury rehabilitation does not take place, or there is an increased pressure to return to play).

There are a limited number of studies investigating previous injury as a risk factor in Rugby Union. Lee et al. (2001b) reported a substantial increase in injury risk for players in the Scottish Border Reivers District league that were injured during pre-season or were injured at the end of the previous season, when compared with non-injured players. Similarly, Quarrie (2001) observed that beginning the season with injury was a significant risk factor for both injury incidence and time lost due to injury in 258 community level Rugby Union players. Interestingly, an injury in the previous season did not significantly increase injury risk, so long as the player entered the following season injury free. These findings highlight the importance of ensuring players are fully rehabilitated before returning to participation. In agreement with these findings, Chalmers et al. (2012) did not find any evidence of an association between a history of injury in the past 12 months and the risk of in-season injury amongst a similar cohort of community level Rugby Union players. As previously stated, these studies relied upon players’ self-reported medical histories, and so may have been subject to recall bias. Moreover, individual

predispositions toward injury were not accounted for, which may have further biased the results. As such, the influence that previous injuries have upon subsequent injury risk in elite Rugby Union remains to be elucidated.

2.8.5 *Anthropometric variables*

Rugby Union teams will typically aim to increase the lean body mass, strength, speed and stamina of their players in order to optimise performance and gain a competitive advantage (Duthie et al., 2006; Garraway et al., 2000). Clear increases in the average mass (~12 kg) and height (~4 cm) of international Rugby Union players since the advent of professionalism have been noted (Sedeaud et al., 2013). In English Premiership Rugby Union teams from 2002 to 2011, there was a trend towards an increase in mean body mass in most positions, although the increase was only statistically significant in fly half and back row players (Fuller et al., 2012b). It has been suggested that muscular players may have greater protection during collisions (Reilly and Hardiker, 1981). Moreover, higher body fat stores may provide an energy absorbing barrier and thus reduce the risk of incurring contact injuries (Meir, 1993), but are likely to have negative associations with the performance of key game behaviours during competition (Smart et al., 2011). Conversely, as the impact force generated in the tackle is a risk factor for injury (Quarrie and Hopkins, 2008), the greater mass and power possessed by larger players may result in their associated contact events having a greater propensity for injury (Fuller et al., 2007b).

A study involving professional Rugby League players concluded that a higher body mass (>95 kg) was indeed associated with increased contact injury risk, whilst findings relating to body fat were unclear (Gabbett et al., 2012a). The frailty model used within this analysis included adjustment for players' age, playing experience and playing position, although an investigation of non-linear relationships was not undertaken. In a prospective whole population study of players competing at the Rugby World Cup in 2007, mismatches in players' body mass had an unclear effect on injury risk (Fuller et al., 2010a). It is likely that this study lacked the statistical power to identify differences in injury risk between the various subgroups of players. Further studies involving amateur Rugby Union players have identified both high Body Mass Index (BMI >25 kg/m²) (Chalmers et al., 2012) and low BMI

(<23 kg/m²) (Quarrie, 2001) as potential risk factors for injury, but these findings are unlikely to be applicable to an elite Rugby Union population. Professional players are likely to be a more homogenous group amongst playing positions in comparison with sub-elite populations (Gabbett, 2006), and professional teams are also likely to have better developed defensive systems, such that large mismatches in body mass between players during contact events are less common. The significant emphasis placed on professional players to possess a high lean body mass alongside minimal body fat is driven by performance requirements and the physical demands of the sport (Warren et al., 2014). Whilst some evidence exists to suggest that heavier players have an increased risk of contact injuries (perhaps due to greater impact forces), and that body fat stores are not a clear indicator of injury risk in collision sports, exploration of this relationship within a larger sample of professional Rugby Union players is necessary. Importantly, the long-term implications of the changes to players' physical characteristics since professionalism, and the concomitant effects on the magnitude and frequency of collisions professional players are subjected to over their playing careers, is worthy of investigation.

2.8.6 Physiological fitness components

Fatigue is often cited as a risk factor for injury in rugby codes (Brooks et al., 2005a; Gabbett, 2008), and so players that are better conditioned may be able to reduce their injury risk. However, such players are also likely to perform more 'work', and so be exposed to a greater number of match events (e.g. tackles) that may increase their overall injury risk. Quarrie (2001) observed that neither anaerobic or aerobic performance, as measured using multistage shuttle tests, significantly influenced injury incidence rates or the proportion of the season missed by amateur Rugby Union players in New Zealand. In professional Rugby League players, the application of a frailty model for recurrent injury data demonstrated that players with poorly developed high-intensity intermittent running ability had a higher incidence rate of contact injuries (Gabbett et al., 2012a). It may be that premature fatigue leads to a reduction in tackling technique, and so an increased incidence rate of tackle injuries (Gabbett, 2008), but it is unclear whether these results can be generalised to professional Rugby Union.

Speed is considered fundamental to success for many positions in Rugby Union (Smart et al., 2011) but high-velocity running may also be associated with an increased risk of both soft-tissue and contact injuries. Fuller et al. (2010a) observed that in differential speed tackles, the player with lower momentum was injured in 80% of cases, indicating that faster players may have an advantage. However, in professional rugby league players, faster players had a higher incidence rate of contact injuries (Gabbett et al., 2012a), whilst the risk of soft-tissue injury was also higher when high-velocity running was performed (Gabbett and Ullah, 2012). Moreover, in amateur Rugby Union players, those in the fastest group (30 m sprint time <3.76 seconds) had a higher injury incidence rate than those in the slowest group (>4.06 seconds), with an incidence rate ratio of 1.51 (95% CI: 0.99-2.30) (Quarrie, 2001). These data suggest that faster players have a higher risk of injury, possibly due to greater contact speeds and impact forces in collisions (Quarrie and Hopkins, 2008). Given that speed is also associated with the performance of key game behaviours in Rugby Union (Smart et al., 2011), the training and development of this physical fitness component requires a cost-benefit consideration for teams. Further physical tests assessed as risk factors for contact injury amongst Rugby League players by Gabbett et al. (2012a) are displayed in Figure 2.9. Well-developed upper body strength (one repetition maximum weighted chin-up) was also found to be protective against contact injuries in these elite collision sport athletes.

Selection pressures at the elite level result in uniformly high physical fitness amongst participants (Smart et al., 2011). Speed, intermittent running ability and upper body strength have been identified as potential risk factors for injury in elite collision sports, although further studies are required to provide greater insight into the role of fitness components upon injury risk in elite Rugby Union players. Ultimately, the development of these characteristics within elite Rugby Union will be driven by performance-related goals. Nonetheless, the possible concomitant effects of such changes (e.g. a greater intermittent running ability may lead to players being involved in more contact events per match) must continue to be monitored from a player welfare perspective.

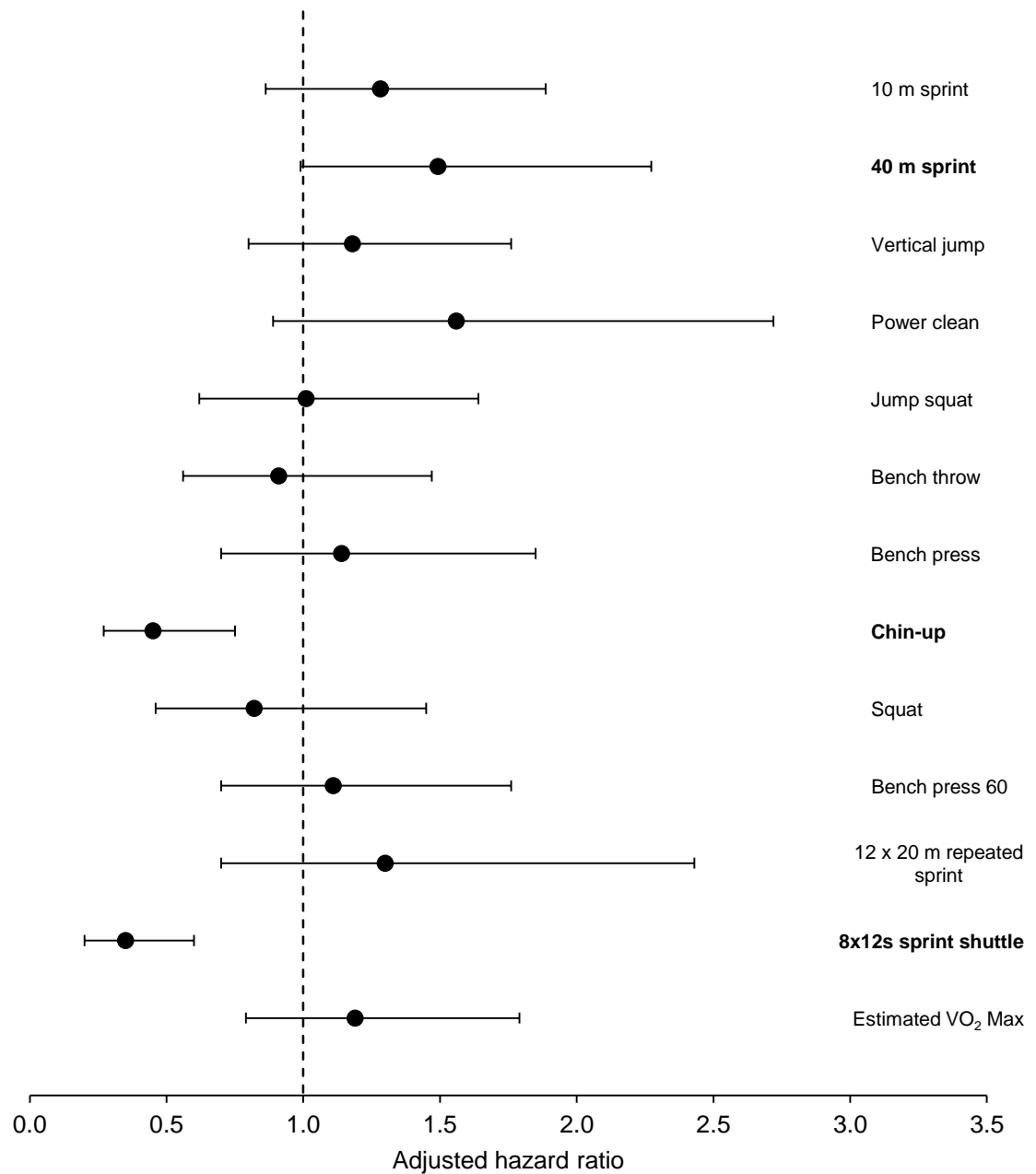


Figure 2.9 Adjusted hazard ratios (with 95% confidence interval) for physical fitness tests as risk factors for contact injury in professional Rugby League players (adapted from Gabbett et al., 2012a). Values represent the effect of well-developed values of the physical test versus lesser developed values (based on dichotomisation according to the median value). Bold values indicate significance at the 10% level.

Extrinsic risk factors

2.8.7 Level of participation

A higher level of play is theorised to be associated with a greater risk of injury. For example, at the elite level match injury incidence rates of up to 218 per 1000 player hours have been reported (Brooks et al., 2005c), whereas in community level rugby injury incidence rates are typically much lower, at around 17 per 1000 player hours (notwithstanding the use of a missed-match definition in these studies compared to a time-loss definition in professional populations) (Roberts et al., 2012). There are a number of proposed explanations for the assumed greater risk of injury at higher levels of participation, including increased size and strength of players (Fuller et al., 2007b), longer seasons (Targett, 1998), higher levels of competitiveness (Jakoet and Noakes, 1998), more efficient injury reporting regimes (Brooks et al., 2005a), greater match speeds (Quarrie et al., 2012) and greater ball-in-play time (Brooks et al., 2005a).

2.8.8 Phase of play

Injury risk appears to vary between different phases of play in Rugby Union. Injuries most commonly occur in the tackle, which have been found to be responsible for up to 59% of match injuries in elite rugby (Bathgate et al., 2002). For tackles injuries, Quarrie and Hopkins (2008) reported that the rate of injury per tackle is highest for tackles from behind, and ball carriers are at highest risk from tackles to the head-neck region, whereas tacklers are most at risk when performing low tackles. Conversely, McIntosh et al. (2010) found no specific tackle technique to be associated with an increased risk of injury. Instead, McIntosh et al. (2010) observed a greater risk of injury for events involving two or more tacklers, and especially those involving simultaneous contact. In a prospective case-control study, one third of injuries were reported to occur in differential speed tackles, with the player with the lower momentum injured in 80% of these cases (Garraway et al., 1999). For training injuries, the greatest risk appears to be associated with fitness testing, rucking and mauling, and defence activities (Brooks et al., 2008).

Fuller et al. (2007b) assessed the propensity of events to cause injury, by calculating the number of days lost per 1000 events. The scrum was found to be the highest risk event, followed by collisions (an illegal tackle in which the tackler attempts to stop

the ball-carrier without the use of their arms), and then tackles. Thus, while the tackle is responsible for the greatest number of injuries, this is due to the fact that the tackle is by far the most common contact event. Scrums and collisions carry a greater risk *per event*, and therefore strategies to improve the safety of these facets of the game may be worthwhile, especially as they may be considered more ‘controllable’ than tackle situations.

Several studies have reported the third quarter of matches to have the highest incidence rate of injury (Bathgate et al., 2002; Best et al., 2005; Fuller et al., 2008; Holtzhausen et al., 2006; Kemp et al., 2011) whilst others have observed the highest injury incidence rate in the final quarter (Brooks et al., 2005a; Fuller et al., 2012a). The lowest incidence of injury rate is commonly observed in the first quarter (Bathgate et al., 2002; Best et al., 2005; Brooks et al., 2005a; Fuller et al., 2008; Fuller et al., 2012a); these results allude to fatigue as an injury risk factor. Moreover, incomplete warm-up or reduced concentration following the half-time break may be factors responsible for the elevated injury incidence rate in the third quarter of matches.

2.8.9 *Playing position*

Differences in injury profile by position have been investigated in several studies. The difference in overall injury incidence rates between forwards and backs is typically negligible (Brooks et al., 2005a; Davidson, 1987; Quarrie, 2001). However, the injury profile of forwards and backs tends to differ. For example, hamstring muscle injuries caused the greatest number of days absence in backs in the English Premiership (for match injuries), but did not feature in the top ten list of injury diagnoses causing the greatest number of days absence in forwards (Brooks et al., 2005a). In order to increase statistical power, many studies have tended to use grouped positions (e.g. front-row forwards), despite there being likely important differences in the physical demands and technical requirements of each playing position (Cahill et al., 2012). Indeed, Brooks and Kemp (2011) observed that while there were no significant differences in total days absence between forwards and backs, there were significant differences in injury profiles between individual playing positions (Table 2.3). This highlights the need for individual position-specific injury-prevention strategies in Rugby Union.

Table 2.3 Injury locations of highest injury risk for players in each playing position in elite Rugby Union (Brooks and Kemp, 2011)

Playing position	Head	Neck	Shoulder	Arm and hand	Chest	Abdomen and thoracic spine	Lumbar spine	Groin/hip/buttock	Thigh	Knee	Lower leg	Ankle/heel	Foot
Loose-head prop		✓	✓		✓					✓		✓	
Hooker		✓	✓							✓	✓	✓	
Tight-head prop			✓				✓			✓		✓	
Second row										✓		✓	
Blind-side flanker			✓						✓	✓			
Open-side flanker		✓	✓							✓		✓	
Number 8			✓	✓						✓			✓
Average forward			✓							✓		✓	
Scrum-half			✓				✓			✓		✓	
Fly-half				✓					✓	✓			
Centres	✓	✓	✓						✓	✓	✓		
Wingers			✓						✓	✓		✓	
Full-back			✓		✓			✓	✓	✓			
Average back			✓						✓	✓			

Injury locations that caused >150 days of absence/1000 player hours, or were significantly greater than the average forward or back, are listed as injury-prevention priorities (✓).

2.8.10 *Ground conditions*

Musculoskeletal injuries are believed to be influenced by the shoe-surface interaction, the parameters of which are likely to differ between various types of playing surface (Drakos et al., 2013). For instance, high frictional forces between the shoe and playing surface may result in foot fixation, which may be a mechanism for lower limb injuries (Olsen et al., 2003). A common finding in both Australian football and European soccer is that the risk of ankle sprains and anterior cruciate ligament (ACL) injuries is higher in teams playing in warmer climate zones, whereas Achilles tendinopathy injuries appear to be more common in teams playing in cooler zones (Orchard et al., 2013). It may be that these injuries have risk factors related to the shoe-surface interaction; a higher traction surface may be a risk factor for ACL and ankle sprain injuries, whereas lower traction (more slippery) surfaces may increase the loading, and thus injury risk, on the Achilles tendon. Whilst these considerations are plausible, more direct experimental data that includes surface traction measures is required. The playing surface may also have an indirect influence on injury risk by changing the nature of the game (e.g. ball-in-play time or running speeds). For instance, Kanaras et al. (2014) reported faster running speeds on new generation artificial surfaces when compared with natural grass in a cohort of young soccer players.

The relationship between ground conditions and injury risk in Rugby Union has been investigated by several authors. The assessment of ground conditions is typically based on broad categorisations (e.g. hard, muddy, soft), with few studies providing further information pertaining to where on the pitch these subjective judgments were made, or the number of locations that were considered. One study that did objectively measure ground hardness, using a penetrometer across 15 standardised areas of the pitch, reported a significant decrease in ground hardness across the course of the season but found no significant relationship between ground hardness and community-level injury risk (Takemura et al., 2007). While harder/drier grounds have been associated with increased injury risk in studies that assessed ground conditions subjectively (Alsop et al., 2005; Gabbett et al., 2007; Ryan and McQuillan, 1992), methodological limitations mean it remains unclear whether the seasonal bias in injury incidence rates often reported in Rugby Union can be directly attributed to ground conditions, or other confounding factors (e.g. match-specific

fitness levels). This finding has been echoed across other football codes (Petrass and Twomey, 2013), and so further research with high quality designs is required.

2.8.11 Playing surface

There is a growing interest in the use of artificial turf surfaces in Rugby Union. Indeed, the International Rugby Board (2008) has published “Regulation 22: Standard relating to the use of artificial playing surfaces”. Currently, few elite professional teams play matches on artificial turf (at the time of writing, only Saracens, Newcastle Falcons and Cardiff Blues in the UK), although several clubs use artificial pitches to allow all-weather training (Stiles et al., 2009). Given the purported benefits of artificial surfaces over natural turf, such as its ability to withstand greater usage, lower maintenance costs and greater consistency across different weather conditions, it is expected that their use by clubs across all levels of the game will increase in the future. However, the injury risk associated with playing Rugby Union on artificial turf is unclear. Fuller et al. (2010b) conducted a two-season investigation comparing match injuries sustained by teams competing in Hong Kong’s Division 1, and training injuries sustained by English Premiership clubs on artificial versus natural turf. Overall, no clear differences were found in the incidence rate of injuries between the two surfaces. A noteworthy finding reported by Fuller et al. (2010b) was that the number of ACL injuries in matches was higher on artificial turf (n=5) compared with natural turf (n=1), but this difference was not statistically significant. This study lacked the statistical power needed to identify clear differences for specific injuries, such as ankle and knee ligament injuries, which have been shown to differ between surfaces in other sports (Williams et al., 2011). Moreover, the study population used from the Hong Kong Division 1 is unlikely to be comparable with that of English Premiership teams, as evidenced by the significant differences in anthropometrics and match injury incidence rates between the two populations (Fuller et al., 2010b). As such, the results may not be applicable to elite Rugby Union cohorts.

Evidence from professional football cohorts suggest that whilst artificial playing surfaces do not appear to influence acute injury risk (Bjørneboe et al., 2010; Ekstrand et al., 2006), when analyses are performed at the team-level, those with artificial playing surfaces installed at their home venues may have a higher rate of

acute training injuries and overuse injuries compared with teams that play home matches on natural grass (Kristenson et al., 2013). Thus, the potential long-term implications of playing on artificial surfaces, and the influence of switching between surfaces, require examination within sporting populations that utilise such surfaces.

There is currently a paucity of biomechanical studies investigating differences in sporting movements between artificial turf and natural grass. Jones et al. (2009) reported greater movement variability of the knee when landing on artificial turf compared with natural grass, which was deemed to be related to the participants' lack of experience on the artificial surface. As such, players lacking experience on artificial surfaces may have an increased injury risk due to non-optimal movement variability. Conversely, Strutzenberger et al. (2014) reported a trend towards a reduction in knee valgus and internal rotation during cutting manoeuvres on artificial turf compared with natural grass, suggesting a reduced risk of knee injury. Consequently, further research is warranted in order to fully understand how the injury risk associated with playing Rugby Union is influenced by playing surface. Specifically, detailed biomechanical analyses and studies of the long-term consequences of playing elite sport on artificial surfaces are required.

A potential barrier to the adoption of artificial surfaces across professional team sports may be the perceived fear of abrasion injuries (Burillo et al., 2012). Wounds, burns and friction injuries were reported to be more common on older generations of artificial turfs compared with natural grass (Ekstrand and Nigg, 1989; Gaulrapp et al., 1999), although new-generation artificial surfaces may present less of a risk, in football cohorts at least (Ekstrand et al., 2011). Yet, the risk of abrasion injuries when playing elite Rugby Union on such surfaces (which likely involves a greater number of player-surface interactions than football) is yet to be elucidated. Abrasion injuries are typically minor, but may result in discomfort and could negatively affect performance (Twomey et al., 2014). Moreover, they can be problematic if foreign materials become embedded in the skin lesion or the area becomes infected (Peppelman et al., 2013). Studies that use time-loss injury definitions are likely to underreport the incidence rate of abrasion injuries. The burden associated with abrasion injuries following elite Rugby Union matches played on artificial playing

surfaces warrants investigation, with special consideration for the method used to identify and report such injuries.

2.8.12 Protective equipment

Rugby Union players wear little protective equipment in comparison with sports such as American football and ice hockey. Research into protective equipment within Rugby Union has centered on the use of headgear, mouth guards and shoulder pads. In a study of New Zealand amateur rugby clubs, 20% of players were reported to wear headgear (Gerrard et al., 1994), while in a study of English Premiership clubs this figure was 7% (Kemp et al., 2008); this value is likely to vary between age groups and skill levels. To date, both field and laboratory based studies have failed to show a clear effect of head guards in reducing the incidence rate of concussion injuries (Benson et al., 2013; Kemp et al., 2008; McIntosh and McCrory, 2000; McIntosh and McCrory, 2001), although the symptoms of concussion for players wearing headgear may be less severe in comparison to those not wearing headgear (Kahanov et al., 2005). Headgear use was also associated with a substantial reduction in superficial head and facial injuries in a case-control study (Jones et al., 2004). As such, the use of headgear may be beneficial as a means of protecting against abrasions and lacerations, but their influence upon the incidence and/or severity of impact injuries (e.g. concussion) is currently unclear.

A meta-analysis of studies investigating the role of mouthguards in preventing orofacial injuries demonstrated a clear benefit for their use in this context (Knapik et al., 2007). However, there is a lack of evidence to support a protective effect of mouthguards against concussion (McCrory, 2001), with studies of sufficient statistical power yet to be performed.

Shoulder pads are typically worn by players to disperse and absorb impact forces, and so potentially reduce the risk of incurring shoulder injuries (Sinclair and Cur, 2009). Whilst shoulder padding has been shown to attenuate peak force at impact during tackles by ~40%, this force attenuation was localised directly above the acromioclavicular joint (Pain et al., 2008). Given that the mechanism for injuries such as dislocations involves force being applied through an abducted arm in combination with rotational force (Gerrard, 1998), the authors suggest that the attenuation of impact forces may not necessarily reduce the risk of injury to this

region. Thus, whilst shoulder pads may reduce the incidence rate of minor soft tissue bruising, there are no data to suggest that shoulder padding will significantly alleviate the risk of more serious injuries (i.e. shoulder fractures or dislocations).

An interesting phenomenon relating to the use of protective equipment is the concept of risk compensation (Hagel and Meeuwisse, 2004). It is postulated that each individual has a set level of risk that they are willing to accept in a given situation; if a player perceives that an intervention has lowered their level of risk (e.g. by wearing shoulder pads), it is theorised that the player will then alter their behavior so as to return to their maximal acceptable level of risk (e.g. by tackling more aggressively). Such changes can negate any beneficial effect of the intervention, and may even result in an increased risk of injury. However, direct evidence to support the existence of this phenomenon is limited, with studies often relying on self-reported behaviors (e.g. Ruedl et al., 2012). McIntosh et al. (2011) were the first to provide quantitative data in a Rugby Union setting, by measuring tackle forces in 98 community level adult players. No clear differences were observed for tackle force with (mean \pm SD; 2025 \pm 695 N) and without headgear (1996 \pm 728 N). Thus, self-reported behavior may not be a reliable guide to actual behavior in this context.

2.8.13 Summary

This section has highlighted the numerous intrinsic and extrinsic factors that may influence an individual player's likelihood of incurring an injury. The paucity of studies specific to elite Rugby Union populations should be noted. This section has also highlighted the changing landscape of injury risk in this sport, as demonstrated by the recent introduction of artificial playing surfaces in professional Rugby Union; this emphasises the need for continued surveillance of injury risk, in order to monitor changes in risk that may occur over time. The large array of risk factors addressed here, alongside the many aspects that were beyond the scope of the present review (e.g. genetic profiles) or are yet to be identified, highlight the complex nature of injury risk in Rugby Union. These facts underline the requirement for analyses that account for unmeasured covariates (e.g. frailty models), as well as more complex approaches (e.g. algorithmic modelling approaches) to best address the multifaceted and complex nature of injury risk in elite Rugby Union.

2.9 Rationale for the current work

This review of literature has highlighted the health, performance, financial and legal arguments for undertaking injury prevention efforts. A number of studies investigating risk factors for injury in collision sports have been published, but few modifiable intrinsic risk factors for injury have been identified. Additionally, a paucity of studies have addressed the need to use appropriate statistical techniques to account for the dynamic and clustered nature of sport injury data. Methods for recording subsequent injuries have been proposed as a means of exploring the extent to which repeated injuries are related, but these have not yet been exploited in Rugby Union cohorts hitherto. The large number of injury risk factors discussed in this chapter, alongside the numerous others that were beyond the scope of this review or are yet to be studied, underlines the fact that individuals may be exposed to varying levels of risk (even after controlling for known risk factors) because of unmeasured or unknown risk factors that cannot be included in a given statistical model. As such, statistical techniques (e.g. the frailty model) that model these unknown covariates are important in this field of study. Additionally, the use of algorithmic modelling approaches to answer research questions pertinent to elite sports is beginning to grow, but such techniques have not yet been utilised in Rugby Union.

CHAPTER THREE

A Meta-Analysis of Injuries in Senior Men's Professional Rugby Union

3.1 Introduction

Rugby Union is now amongst the most played and watched sports in the world, with approximately 6.6 million players in over 117 countries. The inclusion of the shortened version of the game, Rugby Sevens, in the 2016 Olympic Games, alongside the commercial successes of the Rugby World Cup, have contributed to an increase in global participation of more than two million players over the past four years (International Rugby Board, 2014). The game is physically demanding, with frequent bouts of high intensity activity such as running, sprinting, rucking, mauling and tackling, interspersed by periods of low intensity work, such as walking and jogging (Roberts et al., 2008). A range of physical attributes are necessary for elite Rugby Union players, including strength, power, speed, agility and endurance (MacQueen and Dexter, 2010). The combination of high physical demands, alongside exposure to collisions and contacts, means the inherent risk of injury whilst playing Rugby Union is substantial. Indeed, Rugby Union has one of the highest reported incidence rates of match injury amongst all professional team sports (Brooks and Kemp, 2008), although rates are comparable to other full-contact sports such as ice hockey (Lorentzon et al., 1988), Rugby League Gabbett (2005), American Football (Meyers and Barnhill, 2004) and Australian Rules Football (Orchard and Seward, 2002). There have been a number of prospective cohort studies investigating the injuries sustained in senior men's professional Rugby Union since professionalism was introduced in 1995, and the publication of a consensus statement on injury definitions and data collection procedures in 2007 has improved the consistency and quality of research within the field (Fuller et al., 2007c). To enhance the information provided by such epidemiological data, information from several studies may be combined to give more precise effect estimates and increased statistical power (Blettner et al., 1999; Checkoway, 1991). Full understanding of the incidence and aetiology of injuries in professional Rugby Union are the initial steps in the injury prevention model (van Mechelen et al., 1992). To that end, a meta-

Chapter 3

analytic review of senior men's professional Rugby Union injuries was undertaken to collate and summarise the injury data to date, and identify risk factors for injury.

3.1.1 Aim

To review and collate the epidemiological data of injuries in senior men's professional Rugby Union as reported in the literature, and make magnitude based inferences regarding: Level of play; new versus recurrent injuries; playing position; period of match; type of injuries; location of injuries; severity of injuries; and injury incident.

3.2 Methods

Guidelines for reporting meta-analysis of observational studies in epidemiology (MOOSE guidelines) were followed (Stroup et al., 2000). The checklist contains specifications for reporting of meta-analyses of observational studies in epidemiology, including background, search strategy, methods, results, discussion and conclusion.

3.2.1 Literature search

Web of Knowledge, SportsDiscus, PubMed and Google Scholar databases were searched from 1995 through September 2012 using key words 'Rugby Union' and 'inj*'. Furthermore, the reference lists of included studies, and relevant 'grey literature' (e.g. conferences proceedings) were searched to identify additional articles. Inclusion criteria for retrieved studies were set at: (1) Prospective cohort studies; (2) study population comprising of 15-a-side senior male professional Rugby Union teams; (3) studies must give a clear definition of what constituted a reportable injury; and (4) studies must report one or more of the following epidemiological data (i.e. injury incidence rate and/or severity): (i) overall injury incidence rates for match or training injuries; (ii) new and recurrent injuries; (iii) grouped playing position (forwards and backs); (iv) period of match; (v) type of injuries; (vi) location of injuries; (vii) severity of injuries; or (viii) injury incident. Duplicate records were identified and removed. Titles and abstracts of the remaining studies were assessed for relevance, with non-relevant articles being discarded. Full text versions of the outstanding articles were then retrieved and evaluated against the inclusion criteria by two independent reviewers.

3.2.2 Assessment of study quality

Two reviewers independently assessed the reporting quality of included studies using the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement (von Elm et al., 2007). This 22-item checklist provides guidance on the reporting of observational studies, in order to facilitate critical appraisal and interpretation of results. As per Olmos et al. (2008) studies were categorised as either poor, moderate or good based on the percentage of fulfilled items from the STROBE checklist, with cut-off values of <50%, 50-80%, and >80%, respectively.

3.2.3 *Data extraction*

For studies meeting the inclusion criteria, general information pertaining to the level of play, number of participants involved, length of follow-up, and injury definition used within each study was extracted and compiled into a spreadsheet (see Table 3.1). The aim of the present meta-analysis was to determine the overall effects of (i) level of play (international versus level one clubs versus level two clubs); (ii) new versus recurrent injuries; (iii) playing position (forwards versus backs); (iv) period of match; (v) type of injuries; (vi) location of injuries; (vii) severity of injuries; and (viii) injury incident. Thus, multiple rows of data were included for each study to allow for the various combinations of counts and exposures required for each fixed effect. Additionally, a descriptive analysis was provided to describe trends in injury risk over time. Note, shoulder injuries are recorded as ‘upper limb’ injuries within the literature.

The International Rugby Board (IRB) organises its member unions into six tiers according to playing strength and potential (International Rugby Board, 2012); Tier one teams participate in the Six Nations Championship (England, France, Ireland, Italy, Scotland, Wales) or The Rugby Championship (Argentina, Australia, New Zealand, South Africa) while Tier two currently consists of Canada, Fiji, Japan, Romania, Samoa, Tonga and USA. For ‘level of play’, teams were considered to be ‘level one’ if they played in the highest league within a Tier one ranked nation, and ‘level two’ if they played below the top league within a Tier one ranked nation, or in the highest league within a Tier two ranked nation. Where required, authors were contacted to obtain any additional data that was not available in the full text versions.

3.2.4 *Analysis and interpretation of results*

Only studies utilising a ‘time-loss’ injury definition, as outlined by Fuller et al. (2007c), were included in the pooled meta-analysis. A descriptive analysis was provided for studies that could not be included due to incongruent injury definitions. Incidence rate data were modelled using a generalised linear mixed model, with a Poisson distribution and loglinear link function, as previously described (Lystad et al., 2009). The response variable was the number of observed injuries, offset by the log of the number of exposure hours. Severity data were modelled using a general linear mixed model. A random effects term was included to account for the

correlation arising from using multiple rows of data from the same study. Factors of interest were included as fixed effects. The weighting factor used was: (study exposure time [h])/mean study exposure time [h]). Statistical modelling was performed using IBM SPSS Statistics for Windows, (Version 20.0, Armonk, New York, USA).

For injury incidence rate data, the overall estimated means for each fixed effect factor were obtained from the model and then back-transformed to give incidence rates, along with 95% confidence intervals. Comparisons between factors were then made using a spreadsheet for combining effect statistics (Hopkins, 2006b), whereby the incidence rate ratio (and its associated confidence limits) was assessed against pre-determined thresholds. An incidence rate ratio of 0.90 represented a substantially lower injury risk, while an incidence rate ratio of 1.11 indicated a substantially higher injury risk (Hopkins, 2010). For injury severity data, a spreadsheet for deriving a confidence interval and clinical inference from a *P*-value was used (Hopkins, 2007). The smallest practically important effect was a mean difference of 4 d, which was agreed upon by the authors as being likely to impact on team selection. An effect was deemed unclear if its confidence interval overlapped the thresholds for substantiveness; that is, if the effect could be substantial in both a positive and negative sense. Otherwise the effect was clear and deemed to have the magnitude of the largest observed likelihood value. This was qualified with a probabilistic term using the following scale (Batterham and Hopkins, 2006): <0.5%, most unlikely; 0.5-5%, very unlikely; 5-25%, unlikely; 25-75%, possible; 75-95%, likely; 95-99.5%, very likely; >99.5%, most likely (Hopkins, 2007).

3.3 Results

Figure 3.1 displays a summary of the study collection process. The electronic searches returned 355 results. After removing duplicate and non-relevant records, 52 potentially relevant studies were assessed for inclusion in this review, based on the criteria outlined above. Fifteen prospective cohort studies were included, with a methodological quality ranging from poor to good. Older studies tended to have poorer methodological quality than more recent studies (see Table 3.1).

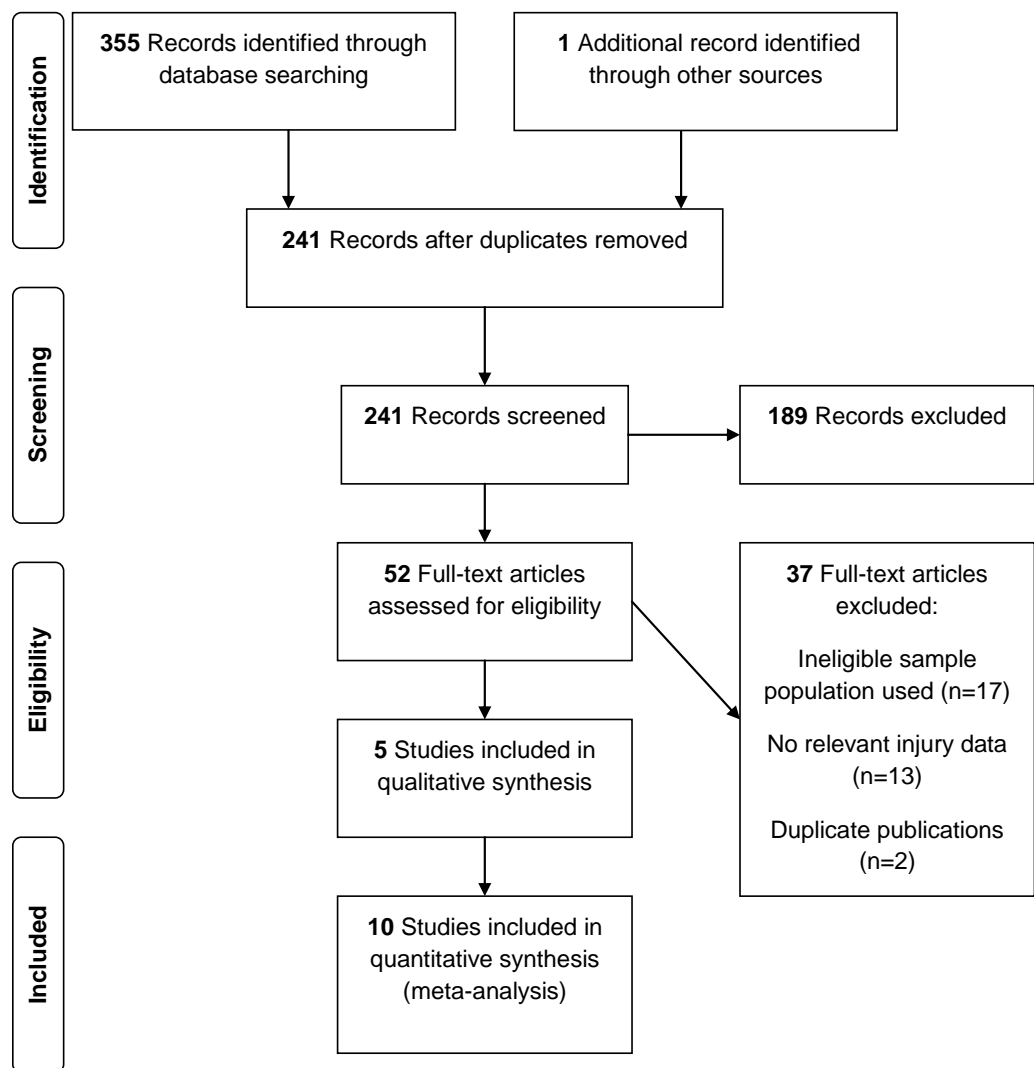


Figure 3.1 Summary of the study collection process for this review, detailing the manner in which studies were identified, screened for relevance, and assessed against inclusion criteria.

3.3.1 *Level of play*

Ten studies (Brooks et al., 2005a; Brooks et al., 2005b; Brooks et al., 2005c; Fuller et al., 2010b; Fuller et al., 2008; Fuller et al., 2009; Fuller et al., 2012a; Garraway et al., 2000; Kemp et al., 2011; Takemura et al., 2011) provided an overall injury incidence rate for either match or training injuries that could be combined in the meta-analysis. The ten studies encompassed a total of 8929 injuries amongst senior male professional Rugby Union players exposed to 656 990 h of match or training time. The overall incidence rate of injuries in senior men's professional rugby matches was 81 per 1000 player h (95% CI: 63-105) and 3 per 1000 player h (95% CI: 2-4) during training. See Figure 3.2 for a summary of the reported match injury incidence rates of the analysed studies. For level of play, the mean incidence rates per 1000 player h with 95% CI were, in descending order: International match: 123 (85-177); level one club match: 89 (75-104); level two club match: 35 (27-45); international training: 3 (2-4), and level one club training: 3 (2-4). The incidence rate during international matches was likely higher (87% likelihood) than during level one club matches and most likely higher (100% likelihood) than level two club matches. Level one club match injury incidence rates were also most likely higher (100% likelihood) than level two club matches. There was no clear difference in incidence rates between international and level one club training injuries. The five studies (Bathgate et al., 2002; Best et al., 2005; Holtzhausen et al., 2006; Jakoet and Noakes, 1998; Targett, 1998) that could not be included in the meta-analysis reported highly variable incidence rates (32-120 per 1000 player h), but in general, incidence rates tended to increase with level of play.

Nine studies (Brooks et al., 2005a; Brooks et al., 2005b; Brooks et al., 2005c; Fuller et al., 2010b; Fuller et al., 2008; Fuller et al., 2009; Fuller et al., 2012a; Kemp et al., 2011; Takemura et al., 2011) provided match injury severity data that could be included in the meta-analysis. The mean severities with 95% CIs for each playing level were, in descending order: Level two club: 23 d (11-34); level one club: 21 d (19-23); international: 20 d (11-28). Differences between levels were unclear.

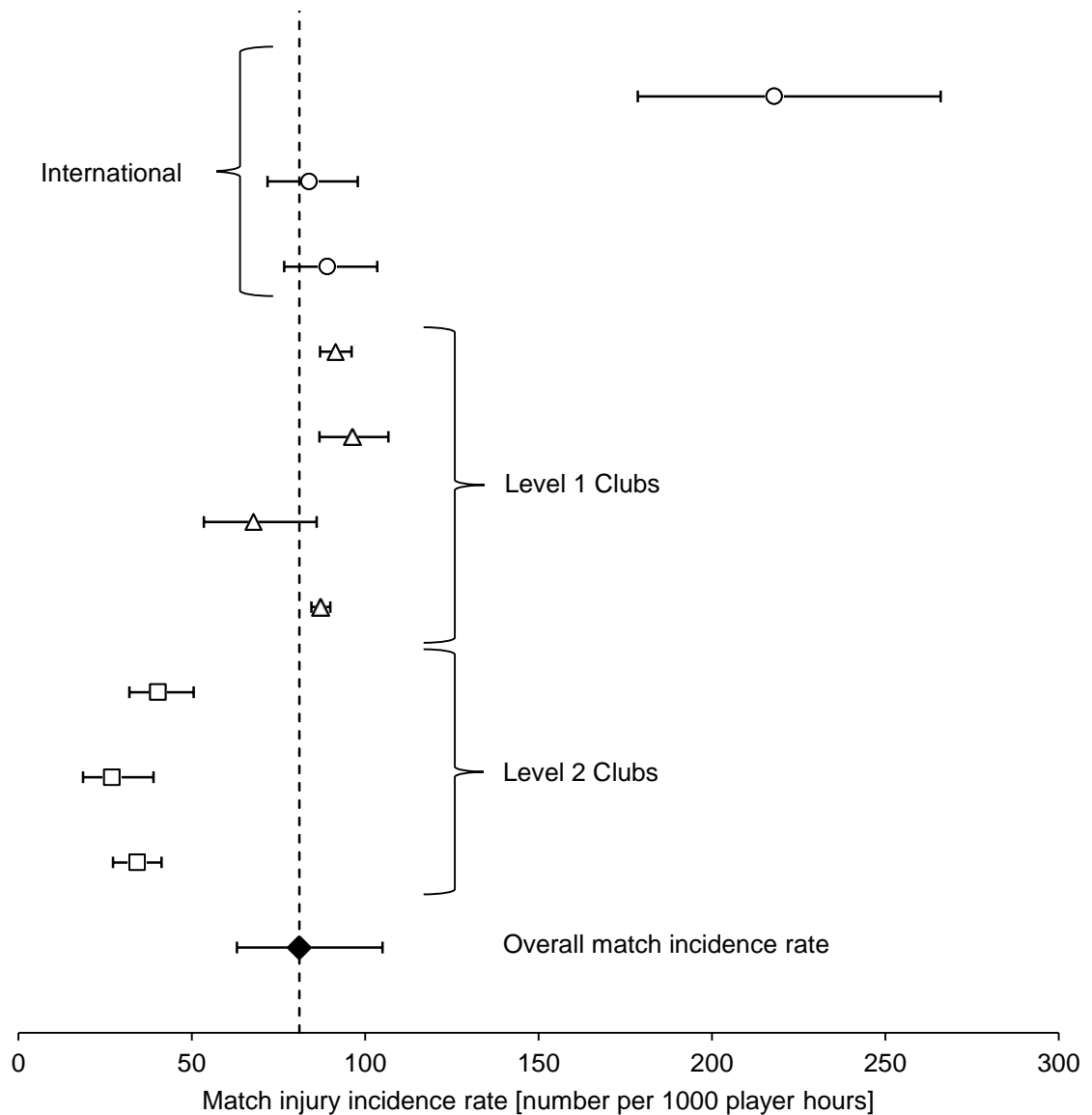


Figure 3.2 Incidence rate of match injuries (with 95% confidence intervals) by playing level for the ten studies included in the meta-analysis, alongside a pooled overall match injury incidence rate for this population.

3.3.2 New versus recurrent injuries

Seven studies (Brooks et al., 2005a; Brooks et al., 2005b; Brooks et al., 2005c; Fuller et al., 2008; Fuller et al., 2012a; Garraway et al., 2000; Kemp et al., 2011) were included in an analysis comparing the incidence of new versus recurrent injuries. The incidence rate of new injuries (78 per 1000 player h, 95% CI: 74-83) was most likely higher (100% likelihood) than that of recurrent injuries (11 per 1000 player h, 95% CI: 10-12). Two studies (Bathgate et al., 2002; Holtzhausen et al.,

2006), which could not be included in the pooled analysis but reported data for new and recurrent injuries, reported similar incidence rate ratios for new versus recurrent injuries (~7.0-9.0).

Four studies (Brooks et al., 2005a; Brooks et al., 2005b; Brooks et al., 2005c; Kemp et al., 2011) provided new and recurrent injury severity data that could be included in the general linear mixed model. Recurrent injuries (30 d, 95% CI: 26-35) were very likely (98% likelihood) more severe than new injuries (20 d, 95% CI: 15-24).

3.3.3 *Playing position*

Six studies (Brooks et al., 2005a; Brooks et al., 2005b; Brooks et al., 2005c; Fuller et al., 2008; Fuller et al., 2009; Fuller et al., 2012a) that reported match injury incidence rates for both forwards and backs were combined in the pooled analysis. There was a 76% likelihood that the difference in the incidence rate of injuries between forwards (94 per 1000 player h, 95% CI: 84-101) and backs (99 per 1000 player h, 95% CI: 92-106) was trivial. Two studies (Bathgate et al., 2002; Best et al., 2005) that could not be included in the pooled analysis due to disparate injury definitions reported trends towards higher injury incidence rates in forwards compared with backs. These studies included injuries that required the player to leave the field of play (e.g. minor skin and laceration injuries); this may account for the observed trend towards a higher injury incidence rates in forwards compared with backs.

Five studies (Brooks et al., 2005a; Brooks et al., 2005b; Brooks et al., 2005c; Fuller et al., 2010b; Fuller et al., 2008) also provided severity data for these grouped playing positions that could be included in the general linear mixed model. There was a likely trivial (80% likelihood) difference in average injury severity between forwards (23 d, 95% CI: 20-26) and backs (21 d, 95% CI: 18-26).

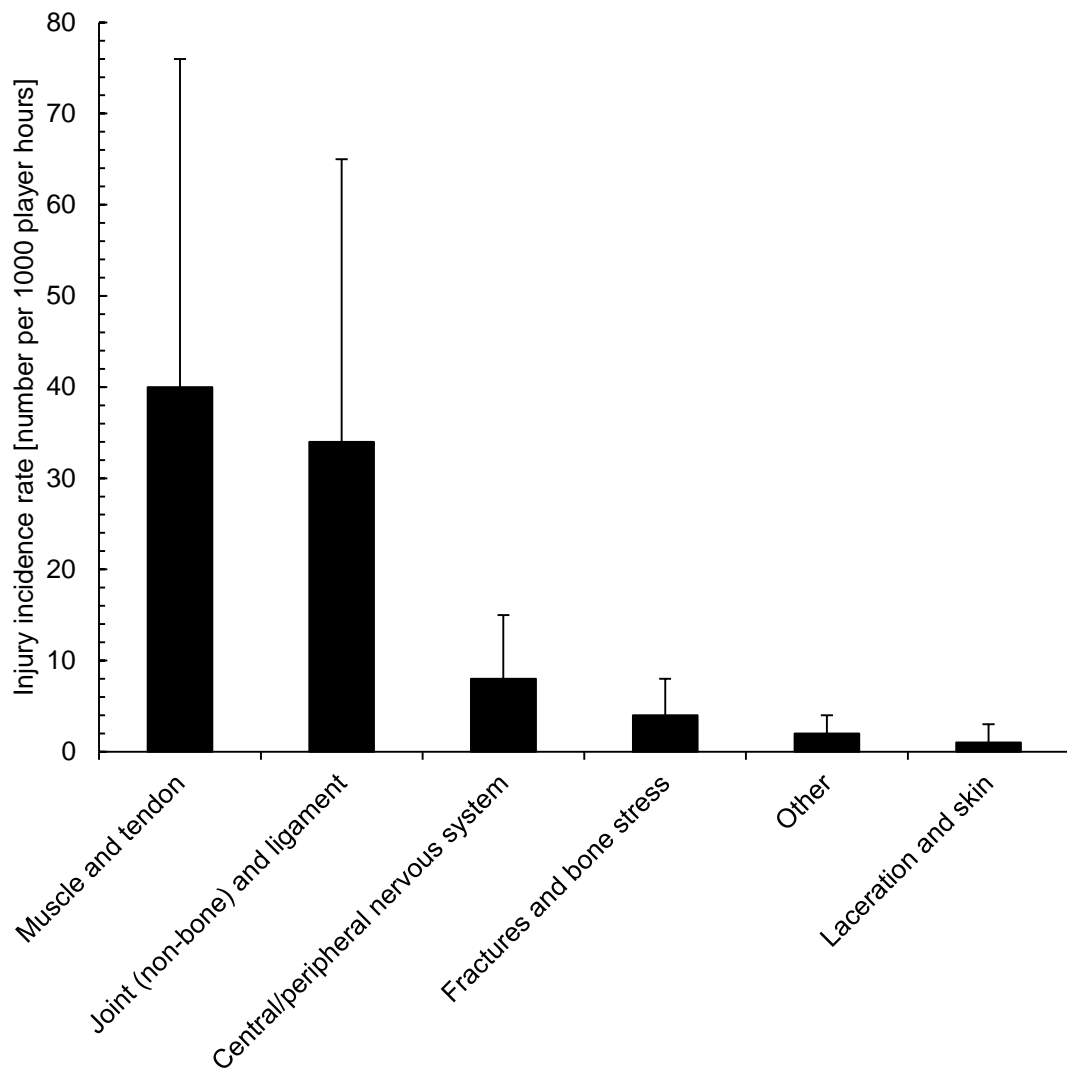


Figure 3.3 Mean injury incidence rates (with 95% confidence intervals) for each injury type (muscle and tendon, joint and ligament, central/peripheral nervous system, fractures and bone stress, other, and laceration/skin injuries) from the six studies included in the pooled analysis.

Table 3.1 Study characteristics, incidence rate of injuries, injury definition and reporting quality of included studies

Study	Sampling time (no. of seasons)	Playing level	Match or training injuries	Number of injuries	Exposure hours	Overall incidence rate (/1000 player h)	Injury definition	Reporting quality
Bathgate et al., 2002	6	International - Australia	Match	Not stated	Not stated	74	Leave field or miss subsequent game	Moderate
Best et al., 2005	1 tournament (7 wk)	International - 2003 World Cup	Match	189	1930	98	Leave field or miss subsequent game	Moderate
Brooks et al. (2005c)	63 weeks	International - England	Match	97	445	218	Time loss	Moderate
			Training	48	7928	6		
Brooks et al. (2005a)	2	Level 1 club -English Premiership clubs	Match	1534	16782	91	Time loss	Moderate
(Brooks et al., 2005b)	2	Level 1 club - English Premiership clubs	Training	395	196409	2	Time loss	Moderate
(Fuller et al., 2008) †	1 tournament (7 wk)	International -2007 World Cup	Match	161	1920	84	Time loss	Good
			Training	60	17046	4		
(Fuller et al., 2009) †	1	Level 1 club - Super 14	Match	362	3760	96	Time loss	Moderate
		Level 2 club - Vodacom Cup	Match	74	1840	71		
(Fuller et al., 2010b) *†	2	Level 2 club - Hong Kong division 1	Match	28	1040	27	Time loss	Moderate
(Fuller et al., 2012a) †	1 tournament (7 wk)	International - 2011 World Cup	Match	171	1020	89	Time loss	Good
			Training	35	15628	2		
Garraway et al., 2000	1	Level 1 club - Border Reivers District (Scotland)	Match	68	1003	68	Time loss	Poor
Holtzhausen et al., 2006	1	Level 1 club – South African Super 12 teams	Match	41	740	55	Time loss, or requiring medical treatment	Moderate
			Training	21	4900	4		

Jakoet and Noakes, 1998	1 tournament (7 wk)	International - 1995 World Cup	Match	70	2194	32	New injury that necessitated the player's leaving the field for the remainder of game	Poor
Kemp et al., 2011 ∞^\dagger	6	Level 1 club - English Premiership clubs	Match	4048	46430	87	Time loss	Moderate
			Training	1626	338367	5		
Takemura et al., 2011 †	2	Level 2 club - Japan Rugby Top League	Match	222	6472	34	Time loss	Poor
Targett, 1998	1	Level 1 club – New Zealand Super 12 team	Match	39	327	120	Missed ≥ 2 training sessions, next match, or requiring medical attention.	Poor

* Injuries sustained whilst playing on artificial turf were not included.

∞ England Professional Rugby Injury Surveillance Project data for seasons for 2005-2011, using methodology outlined by Brooks et al. (2005a).

† Study was implemented according to the 2007 consensus statement for epidemiological studies in Rugby Union.

3.3.4 *Type of injuries*

An analysis was undertaken to determine the most frequent type of match injury sustained (see Figure 3.3). Seven studies (Brooks et al., 2005a; Brooks et al., 2005b; Brooks et al., 2005c; Fuller et al., 2010b; Fuller et al., 2008; Fuller et al., 2009; Fuller et al., 2012a) were included in the pooled analysis. Muscle/tendon (40 per 1000 player h, 95% CI: 21-76), and joint (non-bone)/ligament injuries (34 per 1000 player h, 95% CI: 18-65) were the most common time-loss injury types (with no clear difference between them), followed by central/peripheral nervous system injuries (8 per 1000 player h, 95% CI: 4-15), fractures and bone stresses (4 per 1000 player h, 95% CI: 2-8), unclassified/other (2 per 1000 player h, 95% CI: 1-4), and laceration and skin injuries (1 per 1000 player h, 95% CI: 1-3). Three studies (Bathgate et al., 2002; Best et al., 2005; Jakoet and Noakes, 1998) that could not be included in the meta-analysis reported incidence rates similar to those in our pooled analysis above, although a higher proportion of laceration and skin injuries (23-27%) were found (likely due to the fact that the injury definition used in these studies included injuries that forced a player to leave the field during a match). Note, muscle/tendon and joint(non-bone)/ligament injuries have previously been referred to in extant literature as ‘strains’ and ‘sprains’, respectively.

Four studies (Brooks et al., 2005a; Brooks et al., 2005b; Fuller et al., 2008; Fuller et al., 2012a) also provided severity data for injury types that could be included in the general linear mixed model. Analysis showed that fractures and bone stress injuries (42 d, 95% CI: 32-51) were most severe, with comparisons to all other injury types being clear. The mean severities with 95% CIs of the remaining injury types were, in descending order: Joint and ligament: 29 d (19-39); central/peripheral nervous system: 25 d (16-35); muscle and tendon: 15 d (5-24); other: 12 (2-22) and laceration and skin: 6 d (1-15). Comparisons between these injury types were all clinically clear, with the exception of ‘joint and ligament versus central/peripheral nervous system’, ‘muscle and tendon versus other’ and ‘other versus laceration and skin’, for which inferences were unclear.

3.3.5 *Location of injuries*

Seven studies (Brooks et al., 2005a; Brooks et al., 2005b; Brooks et al., 2005c; Fuller et al., 2010b; Fuller et al., 2008; Fuller et al., 2009; Fuller et al., 2012a) reporting the location of match injuries were pooled in the meta-analysis. Lower limb injuries occurred more often than injuries to other body regions (incidence rate most likely higher [$>99.5\%$ likelihood] for all comparisons). Differences between the remaining body regions were unclear (see Figure 3.4). The mean incidence rates per 1000 player h with 95% CIs of each body region were, in descending order: Lower limb: 47 (26-84); upper limb: 14 (8-25); head: 13 (7-23); trunk: 9 (5-16). The five studies (Bathgate et al., 2002; Best et al., 2005; Holtzhausen et al., 2006; Jakoet and Noakes, 1998; Targett, 1998) that could not be included in the pooled analysis also found the lower limb to be the most frequently injured body region.

Five studies (Brooks et al., 2005a; Brooks et al., 2005b; Brooks et al., 2005c; Fuller et al., 2010b; Fuller et al., 2008) also provided severity data for injury locations that could be included in the general linear mixed model. Analysis showed that upper limb injuries (32 d, 95% CI: 26-38) were most severe, with comparisons to all other body regions being clear. The mean severities with 95% CIs of the remaining body regions were, in descending order: Lower limb: 19 d (13-26); trunk: 16 d (9-22); and head/neck: 12 d (6-18). There was a 76% likelihood that the lower limb injuries were more severe than head/neck injuries, but the remaining comparisons were unclear.

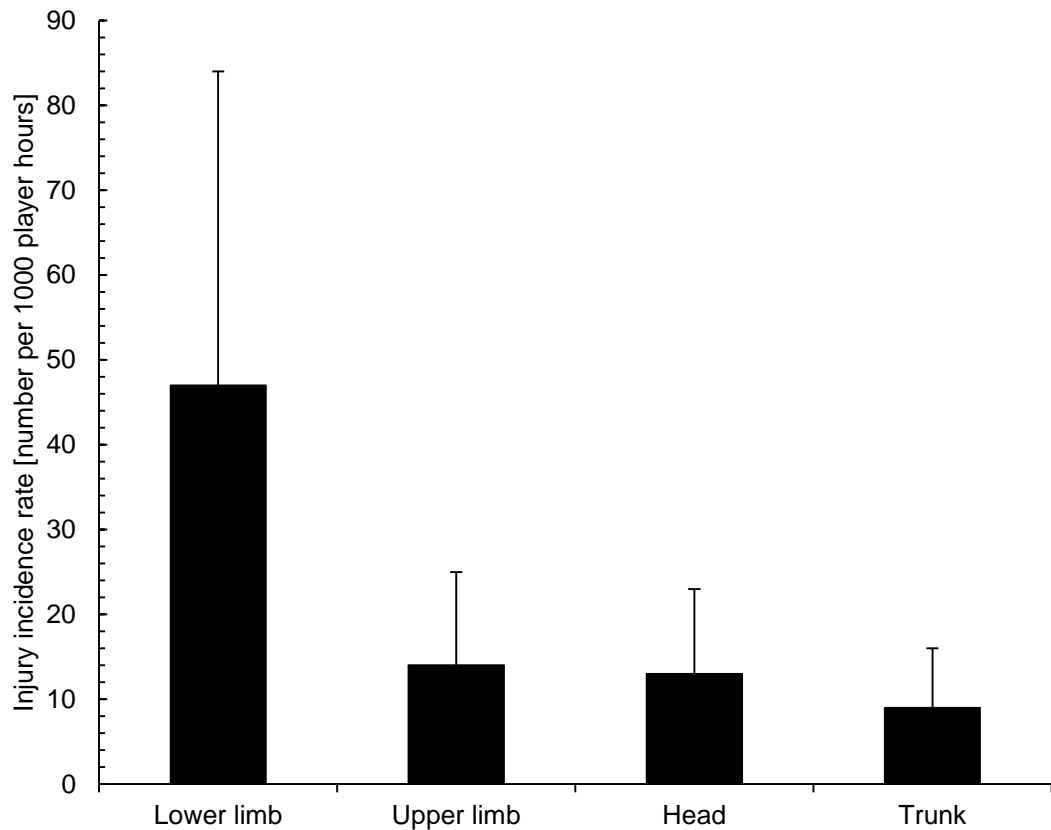


Figure 3.4 Mean injury incidence rate (with 95% confidence intervals) for each injury location (lower limb, upper limb, head, and trunk) from the seven studies included in the pooled analysis.

3.3.6 Severity of injuries

An analysis was undertaken to determine the most frequent severity of injury sustained in senior men's professional Rugby Union matches. Injuries were graded based on time lost from competition and training; minimal (2-3 days), mild (4-7 days), moderate (8-28 days) and severe (>28 days). Five studies (Fuller et al., 2010b; Fuller et al., 2008; Fuller et al., 2009; Fuller et al., 2012a; Kemp et al., 2011) reporting data on the incidence rate of each level of severity were pooled in the meta-analysis. The most common injury severity was 'moderate' (28 per 1000 player h, 95% CI: 25-31), followed by 'mild' (23 per 1000 player h, 95% CI: 20-26), minimal (17 per 1000 player h, 95% CI: 15-19) and 'severe' (15 per 1000 player h, 95% CI: 13-17). Comparisons between each severity level were all clear. Three studies that could not be included in the pooled analysis (Bathgate et al., 2002; Best et al., 2005; Targett, 1998) classified injuries as mild (one game missed), moderate (2-3 games missed) or severe (>3 games missed). Mild injuries were consistently the

most common severity (64-70%), with similar incidences of moderate and severe injuries (14-22%). Holtzhausen et al. (2006) graded injuries according to the number of sessions missed: minor (1-3 missed), intermediate (4-9 missed) and severe (>9 missed). Minor injuries accounted for 39% of all injuries, 27% were of intermediate severity and 34% were severe injuries.

Nine studies (Brooks et al., 2005a; Brooks et al., 2005b; Brooks et al., 2005c; Fuller et al., 2010b; Fuller et al., 2008; Fuller et al., 2009; Fuller et al., 2012a; Kemp et al., 2011; Takemura et al., 2011) reported severity data that could be included in the general linear mixed model. Estimated mean severity for match injuries was 20 d (95% CI: 14-27), and 22 d (95% CI: 19-24) for training injuries; differences between these factors were possibly trivial (70% likelihood). One catastrophic injury (cervical ligament injury) was reported in the reviewed studies (Jakoet and Noakes, 1998).

3.3.7 Period of match

Four studies (Brooks et al., 2005b; Fuller et al., 2008; Fuller et al., 2012a; Kemp et al., 2011) reported injury incidence rates for each match period that could be combined in the pooled analysis (see Figure 3.5). The mean incidence rates per 1000 player h with 95% CIs of each match period were, in descending order: 40-60 min: 119 (108-127); 20-40+ min: 112 (103-121); 60-80+ min: 108 (100-117); and 0-20 min: 57 (51-62). There was a >99.5% likelihood that the incidence rate in the first quarter was most likely lower than the three other match periods. Injuries occurred more often in the third quarter of matches (40-60 min) than other match periods, although the incidence rate was only possibly greater than the second (20-40+ min) and final quarters (60-80+ min), with likelihoods of 28% and 52%, respectively. There was an 83% likelihood that the difference between the incidence rate in the second and final quarters was trivial. Three studies (Bathgate et al., 2002; Best et al., 2005; Holtzhausen et al., 2006) that could not be included in the pooled analysis, but provided period of match incidence rate data, also reported a substantially lower incidence rate in the first quarter compared with the three other match periods, and the highest incidence rate of injury in the third quarter.

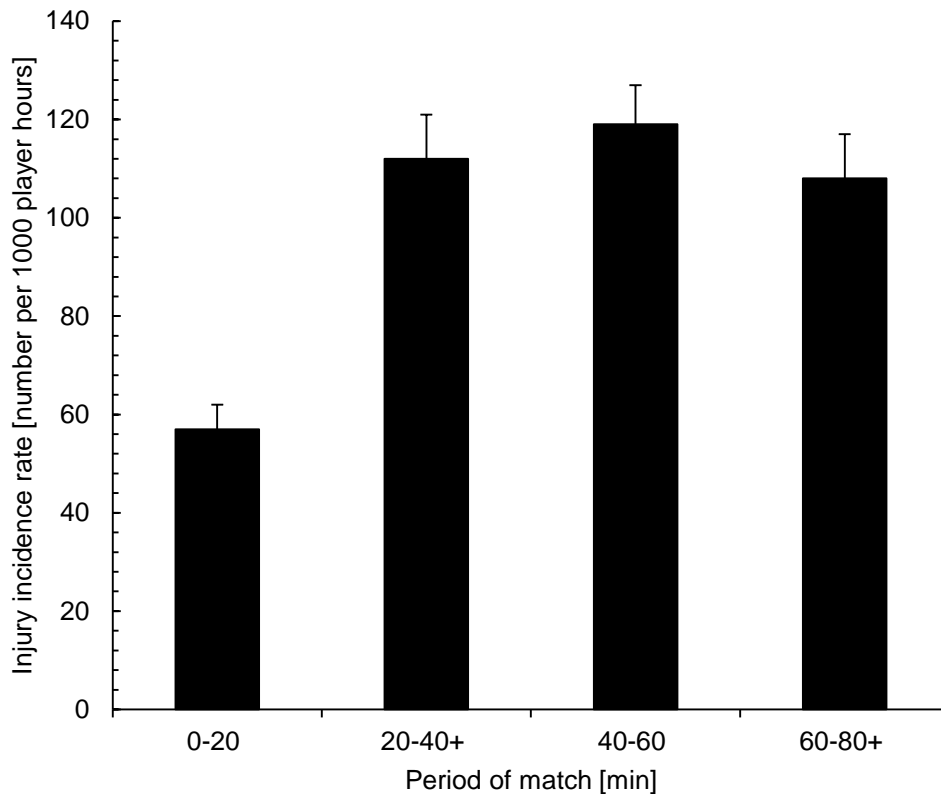


Figure 3.5 Mean injury incidence rate (with 95% confidence intervals) for each match quarter from the four studies included in the pooled analysis.

3.3.8 Injury incident

Five studies (Brooks et al., 2005a; Brooks et al., 2005b; Fuller et al., 2008; Fuller et al., 2009; Fuller et al., 2012a) reporting on the incident resulting in match injuries were included in the meta-analysis. Analysis showed that being tackled (29 per 1000 player h, 95% CI: 19-46) resulted in more injuries than any other incident, with all comparisons being clear (see Figure 3.6). Tackling was the second most frequent injury incident (19 per 1000 player h, 95% CI: 12-29), which was substantially higher than all other match incidents except the ruck/maul (17 per 1000 player h, 95% CI: 11-26), the comparison with which was unclear. The mean incidence rates per 1000 player h with 95% CIs of the remaining match incidents were, in descending order: Collisions: 11 (7-17); scrums: 7 (5-12); other: 6 (3-9); and lineouts: 1 (0-3). Note, exposure to forward specific scrum and lineout injuries was adjusted for appropriately in the analysis. All the remaining comparisons were substantially different, with the exception of ‘other versus scrums’, which was unclear. The five studies (Bathgate et al., 2002; Best et al., 2005; Holtzhausen et al.,

2006; Jakoet and Noakes, 1998; Targett, 1998) that could not be combined in the meta-analysis also reported that the majority of injuries occurred in the tackle phase.

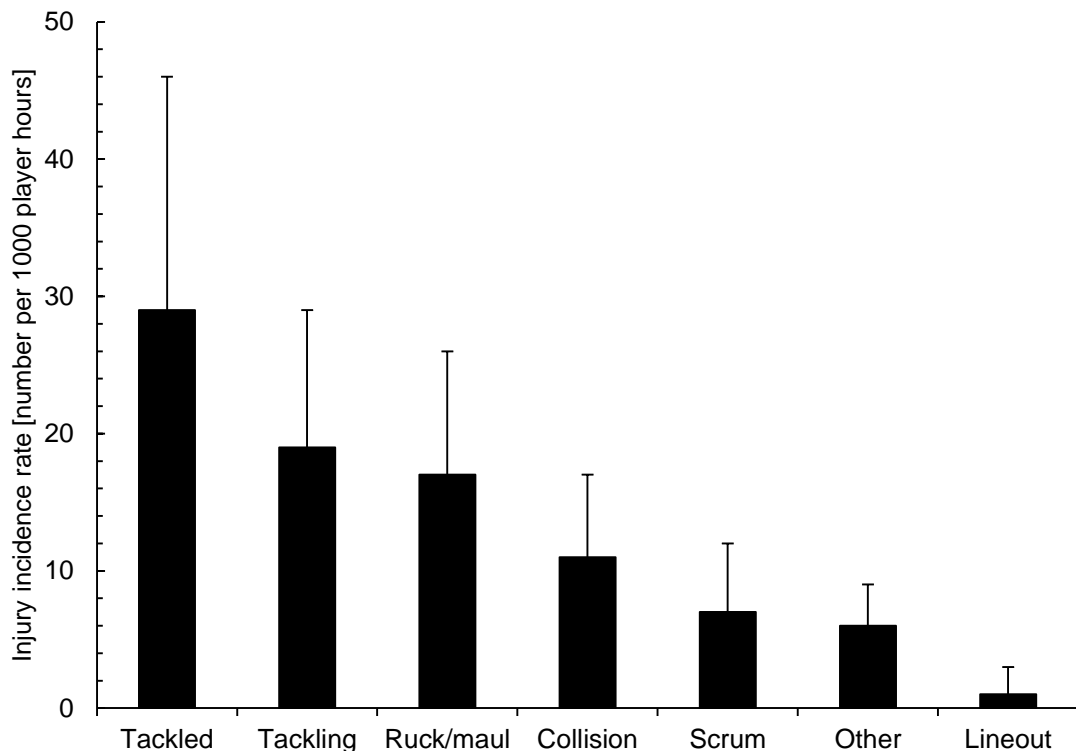


Figure 3.6 Mean injury incidence rate (with 95% confidence intervals) for each injury incident (tackled, tackling, ruck/maul, collision, scrum, other, lineout) from the five studies included in the pooled analysis.

3.3.9 Trends in injury risk over time

Bathgate et al. (2002) reported that incidence rates in the periods before (1994-1995) and after (1996-2000) the start of the professional era in the Australian international team were 47 per 1000 player h and 74 per 1000 player h, respectively. Garraway et al. (2000) reported an increase in the proportion of players injured in senior rugby clubs in the Scottish Borders district, from 27% in 1993-94 to 47% in 1997-1998. The England Professional Rugby Injury Surveillance Project has been used to monitor injuries in Premiership teams since 2002 (Kemp et al., 2011). During this period, the incidence rate of match injuries has remained relatively constant, varying between 75 per 1000 player h (2005-06) to an upper limit of 100 per 1000 player h (2002-03 and 2008-09), with no clear trends apparent. However, a small increasing trend in overall match injury burden (days absence per 1000 player h) was evident, with an average increase of ~53 d per season over this period.

3.4 Discussion

This meta-analysis confirms match injury incidence rates in professional Rugby Union can be considered high in comparison with other team sports but similar to other collision sports. For example, the incidence rate of injuries in international ice hockey was reported to be 79 per 1000 player h (Lorentzon et al., 1988), while Gabbett (2005) reported an incidence rate of 68 per 1000 player h in semi-professional Rugby League players (using a 'missed match' injury definition). The incidence rate of training injuries in Rugby Union is comparable to sports such as soccer (Ekstrand, 2008) and American football (Feeley et al., 2008). By pooling data from several studies that use comparable methodologies, overall estimates of injury data were produced that more accurately reflect the injury incidence rate present amongst this elite population than data provided in individual studies. A higher level of play was associated with a greater incidence rate of injuries in matches, while trivial differences were found in injury incidence rate and severity between forwards and backs. The severity of recurrent injuries was, on average, 10 d greater than new injuries. Muscle/tendon and joint (non-bone)/ligament injuries were the two most prevalent injury groups, whereas fractures and bone stress injuries had the highest average severity. The lower limb was the body region with the highest injury incidence rate, while upper limb injuries were most severe. The first quarter (0-20 min) of matches had the lowest injury incidence rate, and injuries most commonly occurred as a result of being tackled.

In agreement with extant literature (Bird et al., 1998; Jakoet and Noakes, 1998; Targett, 1998), a higher level of play was associated with a greater incidence rate of injuries. International matches had the highest incidence rate, although this was inflated somewhat by one study following the England 2003 Rugby World Cup squad that reported an incidence rate of 218 injuries per 1000 player h (Brooks et al., 2005c). When this study was excluded from the analysis, differences in incidence rates between international and level one club levels became unclear, with incidence rates per 1000 player h with 95% CIs of 90 (75-110) and 91 (84-97), respectively. The overall incidence rate for matches in senior men's professional rugby was also substantially higher than rates previously reported in community rugby (17 per 1000 player h, 95% CI: 16-19) (Roberts et al., 2012), women's elite rugby (36 per 1000

player h, 95% CI: 26-49) (Taylor et al., 2011) and youth elite academy rugby (47 per 1000 player h, 95% CI: 39-57) (Palmer-Green et al., 2013). Proposed explanations for the greater injury incidence rate at higher levels of play include increased size and strength of players, longer seasons, higher levels of competitiveness, more efficient injury reporting regimes, greater distance covered by players at relatively fast running speeds (in excess of 5 m/s) and greater ball-in-play time (Brooks et al., 2005c; Jakoet and Noakes, 1998; Quarrie et al., 2012; Targett, 1998). Moreover, data relating to international teams is typically collected in a tournament setting, which may be inherently different to matches played throughout a seasonal competition. There were no clear differences in the mean severity of injuries between these levels of play. Factors that may influence the reported number of days absence due to injury include the level of medical and rehabilitative care available and the pressure to return to play (Creighton et al., 2010).

New injuries occur substantially more often than recurrent injuries, with the typical incidence rate ratio of new to recurrent injuries being 7:1. There was an exception to this finding among a small sample of players (n=30) during one season in the Border Reivers district club competition in Scotland, where an incidence rate ratio of 0.8 (56% of all injuries were recurrences) was reported (Garraway et al., 2000). While recurrent injuries appear to account for a relatively small proportion of all injuries (~12%), the severity of recurrent injuries appears to be considerably greater than new injuries. This highlights the need to ensure players are fully and effectively rehabilitated before returning to play. However, it should be noted that no studies have directly compared the severity of recurrent injuries to their index injuries; it may be that some types of injury are more likely to reoccur, and if these tend to result in substantial time-loss then the recurrent injury severity figure may be skewed. This warrants investigation in future studies. Fuller et al. (2007a) noted the need to differentiate between 'exacerbations' and 'reinjuries', based on whether a player was fully recovered from the preceding index injury. These authors (Fuller et al.) believe this will enable researchers to investigate risk factors for these two types of recurrent injuries separately, and will also allow them to determine how well players have been rehabilitated before returning to full participation. Further developments in the taxonomy of recurrent injuries have recently been proposed,

with the intention to fully explore the extent to which subsequent injuries (multiple, recurrent, exacerbation or new) are related to previous index injuries (Finch and Cook, 2013; Hamilton et al., 2011a). These proposed developments are yet to appear in published studies.

A trivial difference was found in injury rates and severity between forwards and backs. It may be that greater homogeneity in the nature of involvement in contact events across positions (Quarrie and Hopkins, 2007) has narrowed the gap between these grouped playing positions with regards to injury risk, which had previously been reported to be higher amongst forwards (Best et al., 2005; Holtzhausen et al., 2006; Targett, 1998). However, while no clear differences appear to exist in overall injury profile between these grouped playing positions, Brooks and Kemp (2011) found a number of significant differences in injury profile for players in individual playing positions. Thus, there are likely to be position-specific differences in match injury profiles, determined by the physical and technical requirements of each position (Cahill et al., 2012), which may be used to design more targeted injury-prevention programmes.

The clear finding of a lower incidence rate of injuries in the first quarter in comparison with other match periods may indicate that fatigue is implicated in injury aetiology (Hughes and Fricker, 1994); factors contributing to this (e.g. hydration, nutrition, and biomechanical alterations to technique) require further investigation. For instance, in elite Rugby League players, the quality of tackling technique has been shown to diminish under fatigue (Gabbett, 2008), which may in turn be responsible for fatigue-related tackling injuries. The third quarter (40-60 min) appears to have the greatest incidence rate of injury. Incomplete warm up or reduced concentration following the half-time break may be factors that are implicated in this trend (Bathgate et al., 2002), and so efforts should be made to improve player preparation and to develop strategies for player substitution to alleviate this risk factor. However, the proportion of third quarter injuries sustained by players that started the match versus replacement players has not been reported in the literature; such information may influence any injury prevention strategies.

Muscle/tendon and joint (non-bone)/ligament injuries were the two most prevalent injury groups, whereas fractures and bone stress injuries had the highest average severity; joint (non-bone)/ligament injuries had the highest overall injury burden (a product of incidence rate and severity (Brooks and Fuller, 2006)). The lower limb was the body region with the highest injury incidence rate, while upper limb injuries were most severe; overall injury burden was highest for lower limb injuries. Thigh haematomas and hamstring injuries have been identified as the most common Rugby Union injuries in a previous study (Brooks et al., 2005a), and so these may account for the high burden of lower limb injuries identified in the present review. Thigh haematomas are likely a result of the contact events which are common to Rugby Union (Fuller et al., 2007b), while the requirement for high speed running, accelerations and decelerations within Rugby Union matches may be responsible for the incidence rate of hamstring injuries (Brooks et al., 2005a). Being tackled was the most common injury incident, which is expected given that the tackle is by far the most common contact event in Rugby Union matches (Fuller et al., 2007b). Injuries were most commonly of moderate (8-28 d) severity, which would usually result in players missing between one and four matches.

While there is some evidence to suggest that injury incidence rates increased following the introduction of professionalism in 1995 (Bathgate et al., 2002; Garraway et al., 2000), these studies have noteworthy methodological limitations. Bathgate et al. (2002) reported that incidence rates in the periods before (1994-1995) and after (1996-2000) the start of the professional era in the Australian international team were 47 per 1000 player h and 74 per 1000 player h, respectively. However, no confidence limits were reported for these rates, and this study was limited to just one team. Garraway et al. (2000) reported an increase in the proportion of players injured in senior rugby clubs in the Scottish Borders district, from 27% in 1993-94 to 47% in 1997-1998. However, only 30 professional players were included in this sample, and results are likely to be confounded by rule changes. A small trend towards an increase in overall match injury burden since 2002/03 was found within the England Professional Rugby Injury Surveillance Project (Kemp et al., 2011). However, this finding may not necessarily represent an increase in injury risk for players as injury severity is influenced by multiple 'return-to-play' factors. Indeed, increasing trends

in the number of first team squad players (Fuller et al., 2012b) and reductions in the injury burden caused by recurrent injuries (Kemp et al., 2011) may indicate more effective rehabilitation of injured players, and/or reduced external pressure to return to play. The question of whether injuries in Rugby Union are becoming more common or severe warrants further investigation, across a varied cohort of players.

In order to bring about worthwhile reductions in overall injury burden, efforts should target aspects of the game causing the greatest total absence from playing and training (Brooks and Kemp, 2008). For example, strategies targeting lower limb injury prevention and methods for increasing safe behaviour in contact situations should be considered. Provision of evidence-based information about injury risks and injury prevention strategies to coaches and referees has been successful in reducing injury incidence rates in community rugby (Gianotti et al., 2009); it would be interesting to determine whether such strategies could be effective in increasing safe behaviour in contact situations at the elite level. However, at the elite level there is typically a fine balance to be made between performance optimisation and safety considerations, which may make interventions that directly alter the nature of the game difficult to implement. Efforts to minimise fatigue-induced reductions in tackling technique may be useful in reducing the incidence rate of tackle-related injuries (Gabbett, 2008). Moreover, promising effects of Nordic hamstring strengthening exercises in reducing hamstring injuries have been observed in professional Rugby Union players (Brooks et al., 2006), and so the effectiveness of a large-scale intervention warrants further study.

Methodological limitations were associated with many of the older studies included in this review, namely: variations in injury and severity definitions; a lack of uniform data collection methods; and inclusion of players from only one team (i.e. small sample sizes). Since the 2007 consensus statement (Fuller et al., 2007c), the methodological quality of published studies has improved, allowing for more effective interpretation and comparison of findings across studies. Nonetheless, it is difficult to ensure complete consistency in reporting and data collection practices across studies and teams, as evidenced by one study included in the present meta-analysis that demonstrated a considerably higher match injury incidence rate (218 injuries per 1000 player h) compared to other published studies (Brooks et al.,

2005c). Factors such as the level of motivation, support and time available to data collectors within each team, as well as the nature of the study design and surveillance methodology, will influence the reported injury incidence rates, particularly when considering minor injuries. Providing a breakdown of injury rates by team in multi-team injury surveillance studies would at least allow for some consideration of this effect. Moreover, accounting for clustering by teams within the statistical analyses of such studies would provide more robust (and most likely larger) estimations of variability (Emery, 2007).

A recognised limitation of the present review is that the sample size of studies included was not sufficient to investigate interactive effects within factors (e.g. playing position by level of play). It may be that differences exist between such levels, but these were not accounted for in the present analysis. With continuing injury surveillance amongst this elite population, it is hoped that future studies can add to this data set so that such effects may be investigated. Additionally, while a recent review of tools for assessing the quality of observational studies stated that qualitative checklists were more appropriate than quantitative scales, and that the STROBE statement was a suitable starting point (Sanderson et al., 2007), it should be noted that the STROBE statement was not designed to evaluate the methodological quality of studies, and so may not have been appropriate for assessing the risk of bias in the included studies (von Elm et al., 2007). A further limitation of the present review is that the analysis was weighted towards data provided by the England Professional Rugby Injury Surveillance Project, which may differ substantially to rugby played in other leagues.

The data presented in this review on the incidence and nature of injuries in senior men's professional Rugby Union summarises information relating to the initial steps of the injury prevention model (van Mechelen et al., 1992). During the next step, relevant preventative measures are introduced and evaluated. Large-scale injury prevention programmes have been successfully implemented in community level rugby (e.g. Rugby Smart (Gianotti et al., 2009)) and other football codes (e.g. FIFA 11+ (Steffen et al., 2013)); the application of such measures in an elite professional Rugby Union population should be a priority for future research.

3.4.1 Conclusions

By combining data from a number of prospective cohort studies, it was possible to calculate accurate estimates of injury incidence rates in senior men's professional Rugby Union. The combined analysis reduces potential biases associated with individual studies and variability associated with imprecise estimates (Checkoway, 1991), and so provides an effective overview of the epidemiological data.

The overall incidence rate of match injuries in senior men's professional Rugby Union matches was comparable to rates reported in other team collision sports, while a higher level of play was associated with a greater reported incidence rate of injuries in matches. Recurrent injuries were typically of greater severity than new injuries, and so should be a target for future injury prevention studies. Joint (non-bone)/ligament injuries and lower limb injuries had the highest injury burden for injury group and body region, respectively. The first quarter (0-20 min) of matches had the lowest injury incidence rate, and injuries most commonly occurred as a result of being tackled. Future studies should focus on introducing and evaluating preventative measures that target the risk factors highlighted in this meta-analysis, in order to reduce the injury burden within senior men's professional Rugby Union.

CHAPTER FOUR

Association Between Injuries and Team Success in Elite Rugby Union

4.1 Introduction

It has been proposed that there are two major components of team sports performance: player skill and player durability, and that player durability may be an under-recognised facet of team success (Orchard, 2009). Player durability refers to a player's ability to tolerate the demands of their sport without incurring injuries. Related to this, injury incidence rates and the resulting absence from playing and training in professional Rugby Union is high in comparison with some team sports (Chapter 3). As such, the relationship between injuries and team success in elite Rugby Union may be especially pertinent. Injuries that result in time-loss from training and/or match-play may influence a team's chances of success via a number of mechanisms. For instance, a high injury burden (injury incidence rates \times mean absence per injury) may prevent a coach from selecting the best players for a given match (Hägglund et al., 2013), while there may also be negative psychological effects (for the injured player and/or the team) associated with injury incidents (Ivarsson et al., 2013; Lavalley and Flint, 1996).

A 15-season study involving one French professional football (soccer) team reported no significant relationship between final league position and injury incidence rates (Dauty and Collon, 2011). However, measures accounting for both the frequency and severity of injuries (i.e. injury burden) are likely to be superior for assessing the impact that injuries have upon team success, compared with injury incidence rates alone, because these variables relate more closely to player availability (Brooks and Fuller, 2006; Orchard, 2009). Indeed, in an 11-season study of 24 top European football teams (all teams participated in their countries' highest domestic competition and in UEFA Champions League or Europa League tournaments), a lower injury burden (and thus better match availability) was associated with a higher final domestic league ranking (Hägglund et al., 2013). Further studies in elite football populations have reported significant negative correlations between team success (league ranking) and injury measures such as injury incidence rates (Eirale et al., 2013) and number of injury days per team (Arnason et al., 2004a). While the

Chapter 4

balance of evidence indicates a relationship between injury measures and team success, such evidence is not abundant and more importantly in the context of this study, this relationship has not been investigated within elite Rugby Union.

Providing evidence of a substantial association between injury measures and team success may be useful when attempting to communicate the importance of injury prevention to Rugby Union stakeholders, and when striving to implement injury prevention initiatives within an elite sport setting. Accordingly, the aim of this study was to determine the association between injury measures and the success of professional Rugby Union teams.

4.2 Methods

4.2.1 Study design and setting

A seven-season prospective cohort design was used to record all match and training injuries associated with professional Rugby Union players at 15 English Premiership clubs, according to agreed protocols as part of the Professional Rugby Injury Surveillance Project (PRISP). Injury and exposure data were returned to a study investigator at the academic host institution of the PRISP (2006-2011, Nottingham University; 2011-2013, University of Bath). Data collected from the twelve league teams in each of the seasons between 2006/07 and 2012/13 were collated as part of this Ph.D. This injury database was upheld by the academic host institution of the PRISP.

4.2.2 Participants

All consenting players that were members of the club's first team squad were eligible for inclusion. Data pertaining to a total of 1462 professional Rugby Union players were included in the analysis. The study was approved by the research ethics committee of the academic host institution where the PRISP was based for each season, and written informed consent was obtained from each participant. All data were anonymised.

4.2.3 Variables

The definitions and procedures used in this study were consistent with the international consensus statement for epidemiological studies in Rugby Union (Fuller et al., 2007c). The injury definition used in this study was:

‘Any physical complaint sustained by a player during a first-team match that prevented the player from taking a full part in all training activities typically planned for that day, and/or match play for more than 24 hours from midnight at the end of the day the injury was sustained’.

All injuries were recorded by medical personnel at each club using a modified Orchard Sports Injury Classification System (OSICS) (Orchard, 1995) and standard injury report form. Individual match and grouped training exposure data were

reported weekly by strength and conditioning staff using a standard training report form.

Team injury rates for each season are expressed using injury burden ('overall injury incidence rate \times mean absence per injury', expressed as number of injury days lost per 1000 player hours) in order to account for both the frequency and severity of injuries. As bias may be introduced when combining match and training injury data, due to differences in the ratio of training to match exposure and injury incidence rates between teams (Brooks and Fuller, 2006), injury days per match (total team injury days/number of team matches) was also included as an independent variable in a separate model. The injury days per match variable removes the need to directly combine training and match exposures and injury incidence rates within its calculation, and so was included to verify that inferences made using the injury burden variable were accurate. These measures are likely to capture the impact of injuries to a team, with respect to player availability, in a more complete manner than injury incidence rates alone (Brooks and Fuller, 2006; Orchard, 2009).

Two team success measures were used in the analysis: Premiership league points tally and season average Eurorugby Club Ranking (Eurorugby Club Ranking, 2013). The Eurorugby Club Ranking (ECR) provides an indexed rating of Europe's top teams/provinces competing in France, England, Wales, Scotland, Ireland and Italy, and was included to account for team's performance in European competitions. Each week, the ECR system uses the results of all domestic and European ties and awards points for winning or drawing a match, whilst also making adjustments for factors such as: points conceded and scored, home advantage, strength of opponent, strength of domestic league, importance of the game and recent form. Each team's rating is expressed as a percentage of the top-ranked team. The mean of each team's weekly ECR across the season was included as the team success measure for the season. Descriptive summaries of additional team success indicators (final league ranking, points difference and tries scored) are displayed in Table 4.1.

4.2.4 *Statistical methods*

The analyses used in this study were based on statistical methods employed by Higham et al. (2014) when investigating the association between performance

indicators and match outcomes in international Rugby Sevens. All estimations were made using the *lme4* package (Bates et al., 2008) with R (version 3.0.3, R Foundation for Statistical Computing, Vienna, Austria). Mean values and true between-team and within-team standard deviations (SD) for injury and performance measures were calculated using a mixed-model reliability analysis, with a random effect for team. The between-team standard deviation (representing the stable typical differences between teams) was calculated from the random effect, and the within-team standard deviation (representing the typical variability teams' show between seasons) was calculated from the residual variance.

A linear mixed model was then used to estimate the relationship between the injury and performance measures within each team, whilst allowing for the possibility of individual team differences in this relationship. Injury measures were included as the linear fixed effect, with the performance measure (league points tally or ECR) as the dependent variable, a random effect for team and an interaction effect for injury measure and team. Team squad size (total number of registered players) was included in the model to control for its effect. Additional interaction effects between squad size and injury measures were removed from the model as they did not improve model fit and explained no additional variance in team success. A linear model was used as investigations revealed no evidence of a quadratic relationship between the injury measures and team success. Akaike's Information Criterion and the -2 Log Likelihood were used to assess and compare the model's goodness of fit.

The effect of a change in the injury measure on team success within a team was evaluated by multiplying the slope of the relationship, derived from the linear mixed model, by two within-team standard deviations (Hopkins et al., 2009a). Two standard deviations represents the change within a team from a typically low value of the injury measure (-1 SD) to a typically high value (+1 SD). A between-team effect of the injury measures was assessed by averaging the values of the injury and performance variables across the seven seasons for each team. The effect of the injury measure was then derived by multiplying the slope of the linear relationship between the means by twice the between-team standard deviation of the injury measure.

Inferences regarding the effect of the injury variables were assessed using the smallest worthwhile difference in team success. The smallest worthwhile difference is given by 0.3 of the typical variation of a team's performance from season to season (Hopkins et al., 1999). A spreadsheet was used to calculate the typical variation in league points tally and ECR ranking (Hopkins, 2011). The typical variation for league points tally was nine points, and so the threshold for smallest worthwhile change was set at three points (i.e., 0.3 of the typical variation). Throughout the study period, the average points differential between teams finishing in league position 4th versus 5th (play-off qualification) and 6th versus 7th (European Cup qualification) was also 3 points, supporting its use as a practically meaningful points differential. The typical variation for ECR was 8.81%, and so the threshold for smallest worthwhile change was 2.64%. Effects were classified as unclear if the $\pm 90\%$ confidence limits crossed thresholds for smallest worthwhile difference by $>5\%$, otherwise the effect was deemed clear. All data in text are presented as $M \pm SD$.

4.3 Results

4.3.1 Injury, squad size and team success measures

In total, 883 953 player hours (match, 56 090; training, 827 863) of exposure and 6967 time-loss injuries (match, 4886; training, 2081) were recorded during the study period. This equated to a match injury incidence rate of 87.1 per 1000 player hours (95% CI, 85.1 to 89.2) and a training injury incidence rate of 2.5 per 1000 player hours (95% CI, 2.4 to 2.6). The mean severity of all recorded injuries was 24 ± 41 days. Mean squad size was 45 ± 6 players. Table 4.1 provides a summary of team success and injury measures. Team success measures typically displayed greater variability in differences between teams than changes within teams. For both injury measures, variability in changes within teams was greater than differences between teams.

Table 4.1 Descriptive summary of team success and injury measures

		Mean \pm 90%CI	Observed SD	Within- team SD	Between- team SD
Team success measures	League points tally	49.6 \pm 6.1	15.4	11.1	13.0
	Final league ranking	6.9 \pm 2.4	3.5	2.5	2.6
	Points difference	0.0 \pm 29.5	126.8	86.9	117.8
	Tries scored	41.9 \pm 4.7	11.8	8.1	8.1
	Eurorugby Club Ranking	63.8 \pm 7.8	16.0	10.5	13.6
Injury measures	Injury burden	188.9 \pm 44.3	77.4	67.9	20.1
	Injury days per match	64.5 \pm 6.0	21.9	19.4	6.5

4.3.2 Association between injury measures and team success

The associations between the injury and performance measures are displayed in Figure 4.1. The effect of a 2 SD increase in each injury measure (injury burden and injury days per match) is shown separately for each of the performance measures (league points tally and ECR). All within-team changes and between-team differences in injury measures had a clear substantial negative association with team success measures (83-100% likelihood), with the exception of the effect for between-team differences in injury days per match on ECR, which had an unclear effect (Figure 4.1).

Figure 4.2 displays an example of a strong negative within- and between-team association between teams' injury burden and league points tally. For a typical team, a reduction in injury burden of 42 days per 1000 player h (90% CI: 30-70), or a reduction in injury days lost per match of 16 days (90% CI: 10-36), was associated with the smallest worthwhile change in league points tally (+3 league points). Similarly, a reduction in injury burden of 66 days per 1000 player h (90% CI: 34-644), or a reduction in injury days lost per match of 15 days (90% CI: 9-46), was associated with the smallest worthwhile change in ECR (+2.64%).

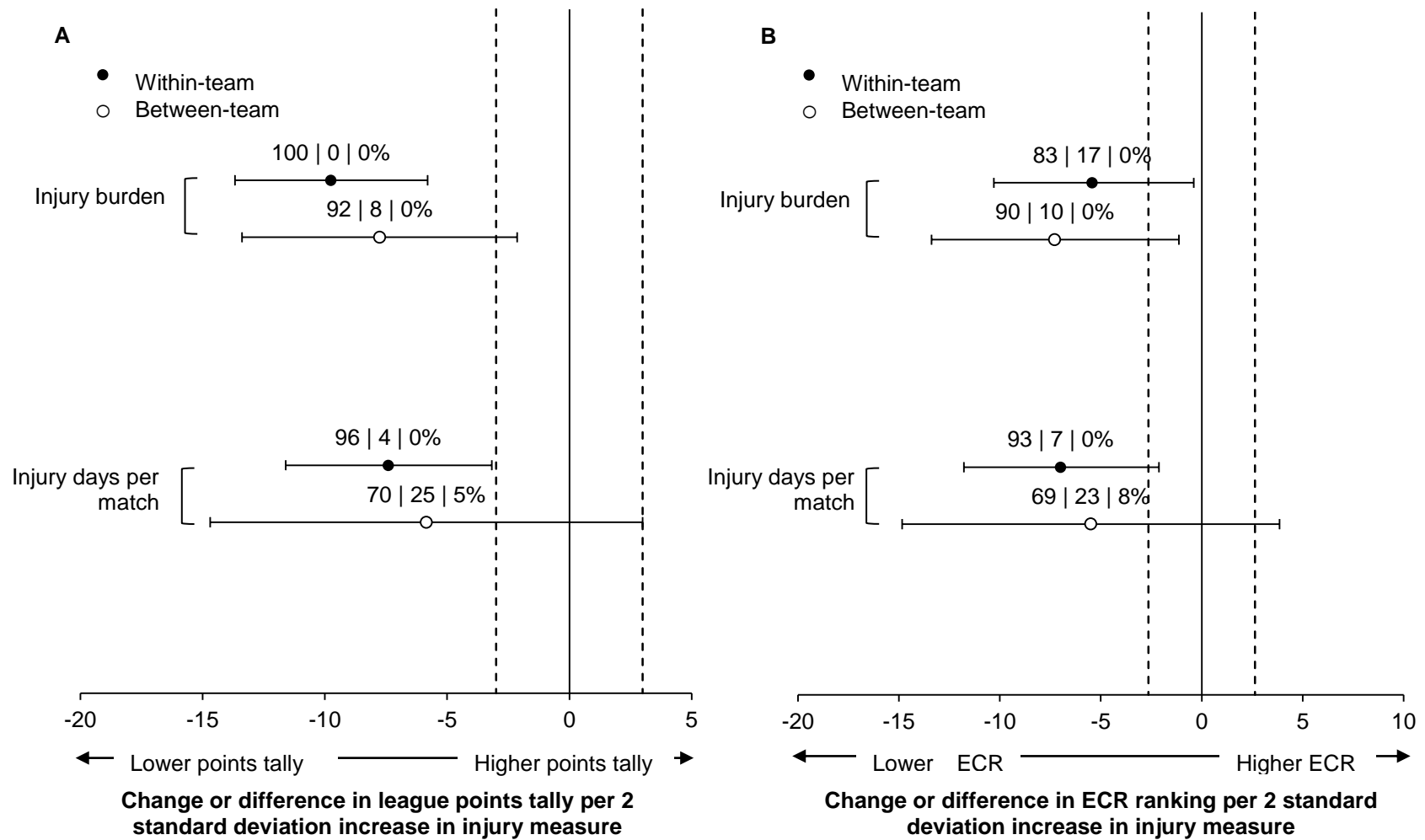


Figure 4.1 Effect of two standard deviations of within-team changes and between-team differences of injury measures on (A) league points tally and (B) Eurorugby Club Ranking. Bars are 90% confidence intervals. Dotted lines represent thresholds for smallest worthwhile difference: (A) ± 3 league points and (B) $\pm 2.64\%$. Data labels give % likelihood that the effect is harmful | trivial | beneficial.

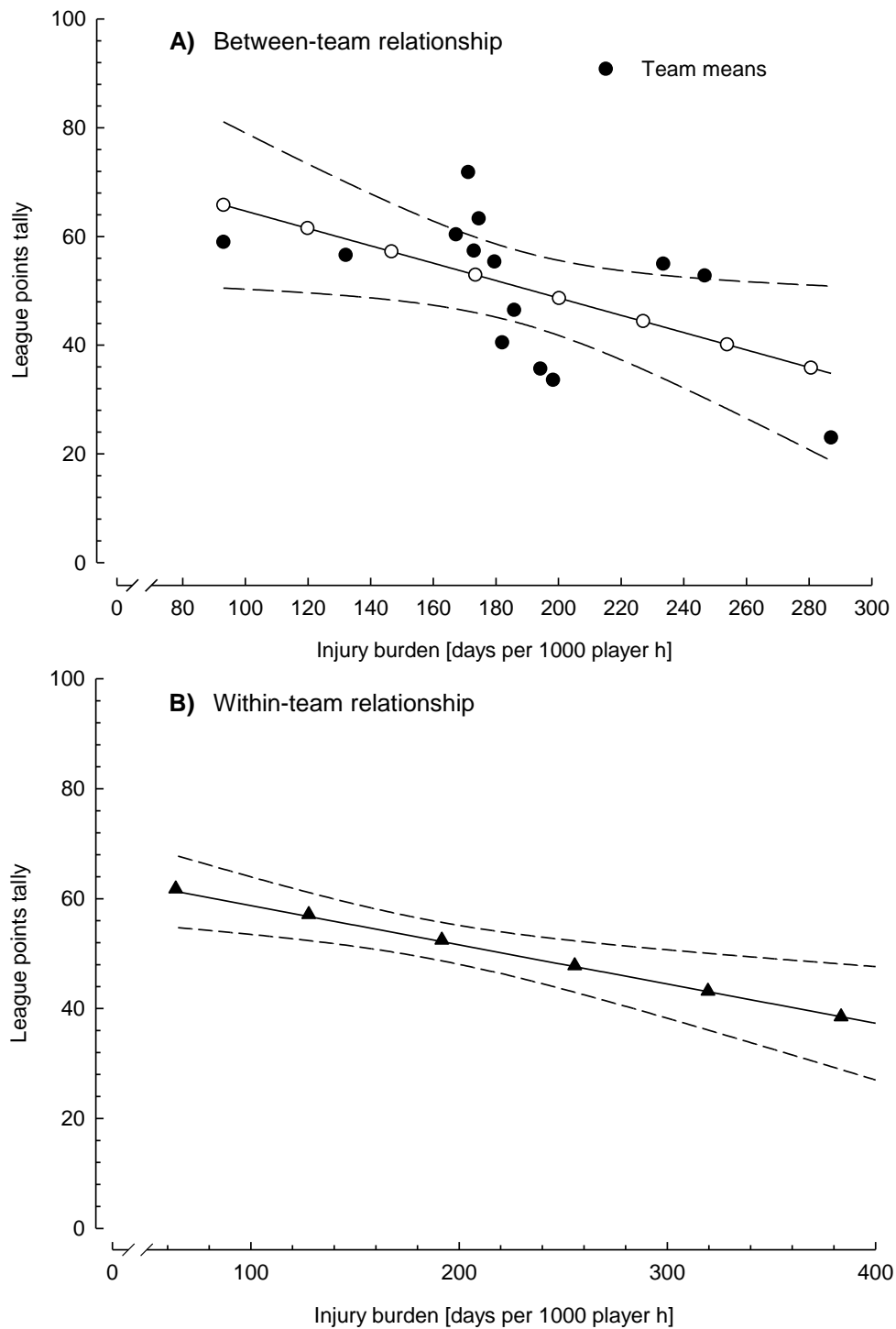


Figure 4.2 Example of strong (A) between- and (B) within-team relationships between an injury measure (injury burden) and team success measure (league points tally). Each filled circle represents the mean value for one of the 15 teams. A best-fitting line is shown for the overall relationship, with dashed lines representing 90% confidence intervals, and symbols representing increments of one between- and within-team standard deviation (open circles and filled triangles, respectively).

4.4 Discussion

This study sought to establish whether there is an association between injury measures and team success in professional Rugby Union. Both injury measures had clear within-team negative associations with league points tally and ECR, such that two standard deviation decreases in the injury measures were associated with substantial (worthwhile) improvements in the team success measures. Between-team differences in injury measures were also associated with team success measures; teams with low injury measure values typically accumulated more league points and had higher ECR rankings.

The results of the current study are in line with previous studies investigating the association between injuries and performance in elite football (soccer) teams (Arnason et al., 2004a; Eirale et al., 2013; Hägglund et al., 2013). The mechanisms through which injuries may be associated with team success are likely to be similar between different team sports; that is, an inability to select the best players for a given match, alongside the potential negative psychological effects (such as stress and anxiety) that may be associated with injury events and may persist when players return from injury (Ivarsson et al., 2013; Lavalley and Flint, 1996). Injury incidents that occur within a given match (and so contribute towards a team's injury burden and injury days per match) are also likely to negatively affect the result of that particular match (Ekstrand et al., 2004b). This may be explained by the fact that the strongest team is typically selected to play, so an injury to any player will weaken the team. Additionally, an injury may require a team to alter their tactical strategy, and may result in players playing out of their favoured position, both of which could reduce the team's chance of winning. These findings highlight the potential importance of injury prevention efforts for improving team success, in addition to the obvious player welfare considerations.

As causality cannot be directly inferred from these findings, it may be that successful teams incur fewer and/or less severe injuries as a result of being successful. Winning teams are typically involved in fewer tackle situations in elite Rugby Union (van Rooyen et al., 2014); since the tackle is the most common injury event (Chapter 3), successful teams are therefore likely to have a lower match injury risk. What is more,

successful teams may have greater budgets available for medical, rehabilitation and strength and conditioning staff and services. In addition, players in poorly performing teams typically experience a greater degree of anxiety (Maynard and Howe, 1987), which may augment their injury risk. For example, tension and anxiety was positively correlated with injury risk in varsity Rugby Union players (Lavallee and Flint, 1996). Moreover, in a study of professional Swedish football players, both negative-life-event stress and ‘daily hassle’ were found to be significant predictors of injury (Ivarsson et al., 2013). Another explanation may be that coaching staff within less successful teams increase training loads in an attempt to improve performances (Foster, 1998). Increasing training loads (a product of the intensity and duration of training sessions) is generally thought to improve athletic performance (Foster et al., 1996), but may also place players at an increased risk of overtraining and injury (Gabbett and Jenkins, 2011). The relationship between training loads and injury risk will be explored in Chapter 8. It is likely a combination of all of these factors that explains the relationship between injury measures and team success found in the current study.

A within-team change in injury burden of ~42 days per 1000 player hours was associated with the smallest worthwhile change in league points tally (± 3 league points). As an illustrative example, this would equate to a typical Premiership team reducing the total number of injuries incurred per season by ~21 injuries (in the context of a mean of 83 injuries per team per season during the study period), or by reducing the average severity of all injuries by ~5 days (in the context of a mean injury severity of 24 d during the study period). One method for achieving such reductions in injury burden may be to allow earlier return-to-play via aggressive rehabilitation strategies for certain injuries (Orchard et al., 2005). However, a more comprehensive understanding of subsequent injuries and the risk of early recurrence in this population is required; this topic will be addressed in Chapter 5. Elsewhere, reductions in injury burden are likely to be best achieved through the targeting of injuries that occur in ‘controllable’ settings (i.e. set-pieces and non-contact injury incidents); on average, 43 injuries per team were sustained in such situations during the 2012/13 season (Kemp et al., 2013). The identification of specific risk factors for injury in this population should be prioritised, so that targeted interventions and

preventative measures can be put in place to facilitate such reductions in injury burden.

The within-team changes associated with the smallest worthwhile change in team success may be used in future studies to evaluate and set thresholds for the effects of injury prevention measures. For instance, as a within-team change in injury burden of ~42 days per 1000 player hours was associated with the smallest worthwhile change in league points tally (± 3 league points), this value may be used to evaluate the performance impact of any injury prevention initiatives within Premiership Rugby Union.

In professional football, the direct and indirect financial costs of injuries have been noted, including the cost of treatment and rehabilitation, the cost of acquiring a replacement player, the cost of reduced performance, the lost revenue from sponsors and supporters, and the cost of the injured players' wages (Drawer, 2001). All of these costs will also apply to professional Rugby Union teams. Indeed, it is estimated that the cost of injured players' wages alone, calculated by multiplying the average weekly Premiership salary by the average total number of matches missed each season due to injury, is approximately £436, 000 per team per season (unpublished observations). As such, there is likely to be a financial benefit to the proactive prevention of injuries (Drawer, 2001). Moreover, clubs and sporting bodies have a clear legal and moral obligation to monitor the injury risk, provide appropriate levels of information regarding that risk, and take preventative measures wherever possible (Fuller, 1995). Clearly, injuries in professional Rugby Union are important from a player welfare, legal and financial perspective, in addition to the presented associations with team success. As such, optimal injury prevention, treatment and rehabilitation should be a priority for all professional Rugby Union stakeholders. Highlighting the clear and substantial negative association between injury measures and team success may be useful when attempting to communicate the importance of injury prevention to Rugby Union stakeholders, and when striving to implement injury prevention initiatives within an elite sport setting.

It should be noted that several potentially important factors were not considered in the current study. For instance, changes in coaching staff and alterations in

training/recovery practices could all moderate the association between injury measures and team success, but the effect of these factors was not included in the present analyses. Moreover, no adjustment was made for the importance that an injured player had within their team; injuries to a team's best players are likely to have a greater impact on team success than injuries to lesser ranked players. Future investigations of the relationship between injuries and team success should therefore consider including a weighting factor that accounts for the importance of a given player within a team. In addition, it should be noted that a given team's success is also dependent on, and relative to, the performances of opposition teams. That is, a team may improve underlying aspects of their performance (e.g. physical conditioning and technical skills) from one season to the next but, if opposition teams improve to a similar or greater extent, then their likelihood of success may remain unaltered.

4.4.1 Conclusion

The present study is the first to investigate the association between injuries and team success in elite Rugby Union. Clear negative relationships were found between injury measures and team success, and moderate reductions in injury burden could potentially have a worthwhile effect on competition outcomes for these elite teams. These findings highlight the important role that medical, rehabilitation and strength and conditioning staff have in reducing the incidence and/or severity of injuries in order to improve team success.

CHAPTER FIVE

Distribution and Severity of Subsequent Injuries in Elite Rugby Union: Application of the Subsequent Injury Definition

5.1 Introduction

Injury incidence and the resulting absence from playing and training in elite Rugby Union is high in comparison with some team sports (Chapter 3). Moreover, the results of Chapter 4 have shown there to be a negative association between injuries and team success. As well as preventing the initial occurrence of injuries (primary injury prevention), an important aspect of injury prevention programmes is to minimise the occurrence of subsequent injuries (secondary injury prevention). Typically, all injuries that succeed an initial injury are classified as subsequent injuries, whilst injuries to the same site and of the same type as an index injury are defined as recurrences (i.e., a subcategory of subsequent injuries) (Fuller et al., 2007c). Approximately 14% of all match time-loss injuries incurred by elite Rugby Union players are categorised as recurrent injuries (Chapter 3).

US high school athletes were three times more likely to choose to discontinue sport participation after incurring a recurrent injury, in comparison to incurring a new injury (Swenson et al., 2009). In addition, the average severity of recurrent injuries has been shown to be substantially higher than new injuries across a number of populations (e.g. Chapter 3; Hawkins and Fuller, 1999; Rauh et al., 2007; Waldén et al., 2005). However, it should be noted that these studies compared the severity of recurrent injuries to all other injuries, rather than directly with the associated index injury of the given athlete. The question of interest for many practitioners and researchers is whether the severity of subsequent injuries, particularly to previously injured body sites, are typically greater than the associated index injury. This question remains to be answered within a Rugby Union cohort. Thus, there is a clear need to specifically study subsequent injuries within this population, using an appropriate analysis strategy.

The consensus statement on injury definitions in Rugby Union includes a classification relating to the time between return-to-play from an index injury and a

recurrence (<2 months, 'early'; 2-12 months, 'late'; >12 months, 'delayed') (Fuller et al., 2007c), but no data using these categories within Rugby Union cohorts has been published. Other professional team sports have reported that a high proportion of recurrent injuries (78-93%) occur within two months of return-to-play (Häggglund et al., 2007; Häggglund et al., 2009a; Häggglund et al., 2009b). Identifying the types of injuries that are associated with an increased risk of early recurrence may help guide practitioners towards more effective treatment, rehabilitation and return-to-play assessments for these injury diagnoses.

Recently, further developments in the taxonomy of subsequent injuries have been proposed, with the intention to fully explore the extent to which subsequent injuries are related to previous index injuries. Hamilton et al. (2011a) applied the 'Subsequent Injury Definition' to a cohort of circus performers, whereby a subsequent injury after an index injury was classified as (1) new injury: different site; (2) local injury: same site; or (3) recurrent injury: same site and type. Further to this, Finch and Cook (2013) presented the 'Subsequent Injury Classification' model, with ten different dependency structures between injury types. The 'Subsequent Injury Classification' scheme also allows for different and multiple index injuries, rather than only using the first injury in a player's chronological sequence. In effect, the 'Subsequent Injury Classification' model splits each of the previous classification categories (based on Hamilton et al.'s classification) into two groups: 'related to index injury' or 'not related to index injury', alongside a category for injury mechanism (acute or overuse) relating to injury recurrences (exact same injury in terms of body site and nature). However, there has been some debate within the literature as to the merit of these additional variables.

Shrier and Steele (2013) advise that incorporating an *a priori* subjective assessment of whether an injury is related to a previous index injury is likely to underestimate the total causal effect of the index injury, and would require the assessors to be blinded to the research question. As an example, Finch and Cook (2013) present a case where the index injury was a fully healed fractured leg that occurred due to a blow, whilst the subsequent injury was a second fracture after the index injury had fully healed. Finch and Cook (2013) classify this as an 'exact same injury in terms of body site and nature, not related to an index injury'. In contrast, Shrier and Steele

(2013) highlight that the subsequent injury may have resulted from impaired proprioception due to the index injury, and, by using the Subsequent Injury Classification scheme the relationship between the two would not be identified because *a priori*, it had been decided that the two were not related. Moreover, the subjective nature of decisions regarding the causal effect of index injuries will be subject to issues of reliability and validity. As such, the additional fields incorporated within the Subsequent Injury Classification scheme do not appear to provide any additional benefit over the Subsequent Injury Definition. Thus, the Subsequent Injury Definition appears the best available approach for categorising subsequent sports injuries.

Identifying causal relationships between injuries is important from an injury prevention perspective, as specific strategies may be needed to prevent the occurrence of injuries that are related to previous injuries (e.g. improved injury rehabilitation processes) (Finch and Cook, 2013). Whilst a number of descriptive epidemiology studies have been conducted within elite Rugby Union, none have specifically addressed subsequent injuries. As such, the aim of this study was to describe the distribution and severity of subsequent injuries within elite Rugby Union players, through the application of the Subsequent Injury Definition.

5.2 Methods

5.2.1 Study design and setting

An eight season prospective cohort design was used to record all match and training injuries associated with elite Rugby Union players at 15 English Premiership clubs, according to agreed protocols as part of the Professional Rugby Injury Surveillance Project (PRISP). Injury and exposure data were returned to a study investigator at the academic host institution of the PRISP (2005-2011, Nottingham University; 2011-2013, University of Bath). Data collected between the 2005/06 and 2012/13 seasons were collated as part of this Ph.D. This injury database was upheld by the academic host institution of the PRISP.

5.2.2 Participants

All consenting players that were members of clubs' first team squads were eligible for inclusion in the study. Data pertaining to a total of 1555 elite Rugby Union players were included in the analysis. The study was approved by the research ethics committee of the academic host institution where the PRISP was based for each season, and written informed consent was obtained from each participant. All data were anonymised.

5.2.3 Variables

The definitions and procedures used in this study were consistent with the international consensus statement for epidemiological studies in Rugby Union (Fuller et al., 2007c). The injury definition used in this study was:

‘Any physical complaint sustained by a player during a first-team match or training session that prevented the player from taking a full part in all training activities typically planned for that day, and/or match play for more than 24 hours from midnight at the end of the day the injury was sustained.’

All injuries were recorded by medical personnel at each club using a modified OSICS system (Orchard, 1995) and standard injury report form. Each injury was assigned to a bespoke grouping based on its Orchard code (Brooks et al., 2005a).

Subsequent injuries (i.e. all injuries that a player incurred subsequent to an initial injury) were classified retrospectively using the ‘Subsequent Injury Definition’

(Hamilton et al., 2011a). The Subsequent Injury Definition process is outlined in Figure 5.1. The number of days between returning to full training and/or match participation and the occurrence of a subsequent injury was calculated for each subsequent injury ('time to subsequent injury'). As per the recommendation of Finch and Cook (2013), different and multiple index injuries were allowed. A player's first recorded injury within the database was considered an index injury. In cases where players sustained the same local or recurrent injury multiple times, the most recent previous occurrence was used as the index injury in each case. For new injuries (a subsequent injury to a new body location, i.e., one that the player had not injured previously), the player's most recent previous injury was used as the index injury.

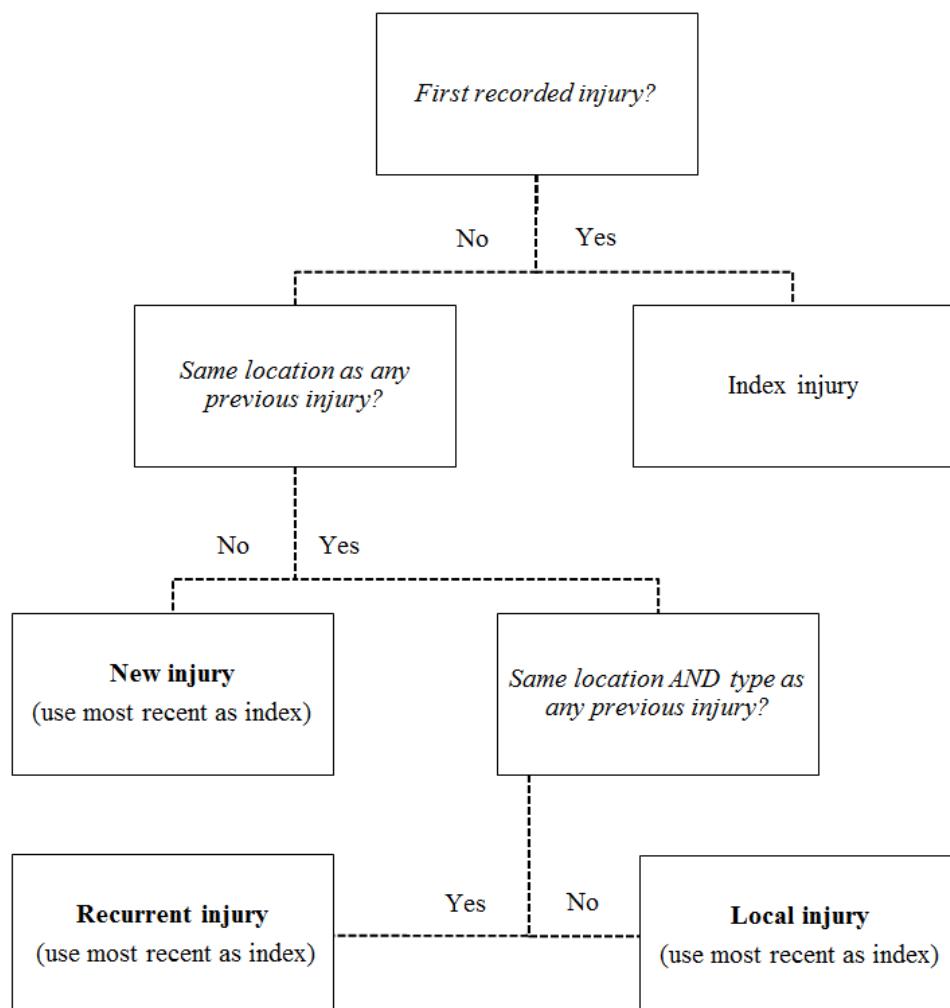


Figure 5.1 Subsequent Injury Definition process (adapted from Hamilton et al., 2011a). Subsequent injuries were defined as: New (different site); Local (same site and different type); or Recurrent (same site and type).

In line with the consensus statement on injury definitions and data collection procedures for studies of injuries in Rugby Union (Fuller et al., 2007c), subsequent injuries were classified according to when they occurred after return-to-play from the index injury: early (< 2 months), late (2-12 months) and delayed (>12 months).

5.2.4 Statistical methods

A two-step cluster procedure was performed on the ‘time to subsequent injury’ variable for all recurrent and local injuries, to identify any groupings within the data in relation to the time delay between index and subsequent (local and recurrent) injuries. Step one of the two-step algorithm involved the formation of pre-clusters, whereby a sequential clustering approach was used to decide if each record should be merged with previously formed clusters or entered into a new cluster, based upon a Euclidean distance criterion. In step two, the algorithm merged the sub-clusters into the optimal number of clusters via a hierarchical clustering process. In this process, all sub-clusters were compared and the pair with the smallest distance between them were merged into a single cluster; this process was repeated until the optimal number of clusters had been formed, as defined by a Bayes information criterion (BIC). The two-step cluster procedure was chosen for its ability to handle large datasets (Zhang et al., 1996), and was performed using IBM SPSS Statistics for Windows, Version 20.0 (Armonk, New York, USA). Cluster validation was assessed via the silhouette coefficient [equation 5.2], which measures the cohesion and separation of the formed clusters (Aranganayagi and Thangavel, 2007). Firstly, silhouette $s(x)$ was calculated using equation 5.1:

$$s(x) = \frac{b(x) - a(x)}{\max\{a(x), b(x)\}} \quad \text{Eq. 5.1}$$

Where $a(x)$ was the average distance of x to all other vectors in the same cluster, and $b(x)$ was the average distance of x to the vectors in other clusters. Subsequently, the silhouette coefficient (SC) was calculated using equation 5.2. The average silhouette coefficient was assessed using the following scale (Struyf et al., 1997): <0.2, poor; 0.2-0.5, fair; >0.5, good.

$$SC = \frac{1}{N} \sum_{i=1}^N s(x) \quad \text{Eq. 5.2}$$

For each injury diagnosis grouping, the ‘proportions test’ in R (version 2.15.1, R Foundation for Statistical Computing, Vienna, Austria) was used to test whether the proportion of cases within the cluster with the lowest mean time to subsequent injury (‘early recurrence’ cluster) was substantially greater than expected. Only injury diagnosis groupings for which there were a sufficient number of cases to allow for normal approximation were evaluated. Specifically, equation 5.3 was used, where n was the number of cases and p represented the proportion of cases in a given cluster. A value of $X > 10$ was required for the injury diagnosis grouping to be included in the analysis (Hunter and Hunter, 1978):

$$X = n(1 - p) \quad \text{Eq. 5.3}$$

The resultant proportion and 90% confidence intervals were evaluated using magnitude based inferences (Hopkins et al., 2009a); the smallest worthwhile difference in frequencies was $\pm 10\%$ of the overall proportion of injuries in each cluster (Hopkins, 2002). Thus, a ‘harmful’ effect represented an injury diagnosis that was over-represented within the early recurrence cluster, whilst a ‘beneficial’ effect represented an injury diagnosis that was under-represented within the early recurrence cluster.

Similarly, the effect size for differences between the severity of subsequent injuries and the severity of their related index injuries was assessed using magnitude based inferences. Effect sizes were interpreted with the following scale: <0.2 , trivial; 0.2 to 0.6 , small; 0.6 to 1.2 moderate; and >1.2 , large (Hopkins et al., 2009a). Clinical inferences were made, such that an effect was deemed unclear if the chance that the true value was beneficial was $>25\%$, with odds of benefit relative to odds of harm (odds ratio) of <66 (or vice versa). Otherwise, the effect was deemed clear. The odds ratio of 66 ensured that an effect with a $>25\%$ chance of benefit and $<0.5\%$ of harm was a decisively useful effect (Hopkins et al., 2009a).

5.3 Results

5.3.1 Subsequent injury counts

In total, 9597 time-loss injuries (match: 6903, training: 2617) were recorded during the study period. Of these, 8180 (85%) were subsequent injuries (match: 6063, training: 2087). The total number of players participating in each season was 548, 352, 543, 505, 522, 553, 581, and 596, respectively. Figure 5.2 shows the number of subsequent match and training injuries within each Subsequent Injury Definition category (new, local and recurrent) over the study period. Overall, the majority of subsequent injuries (70%) were classified as new injuries (different site), with 14% local (same site as a previous injury but different type) and 16% recurrent (same site and type as a previous injury).

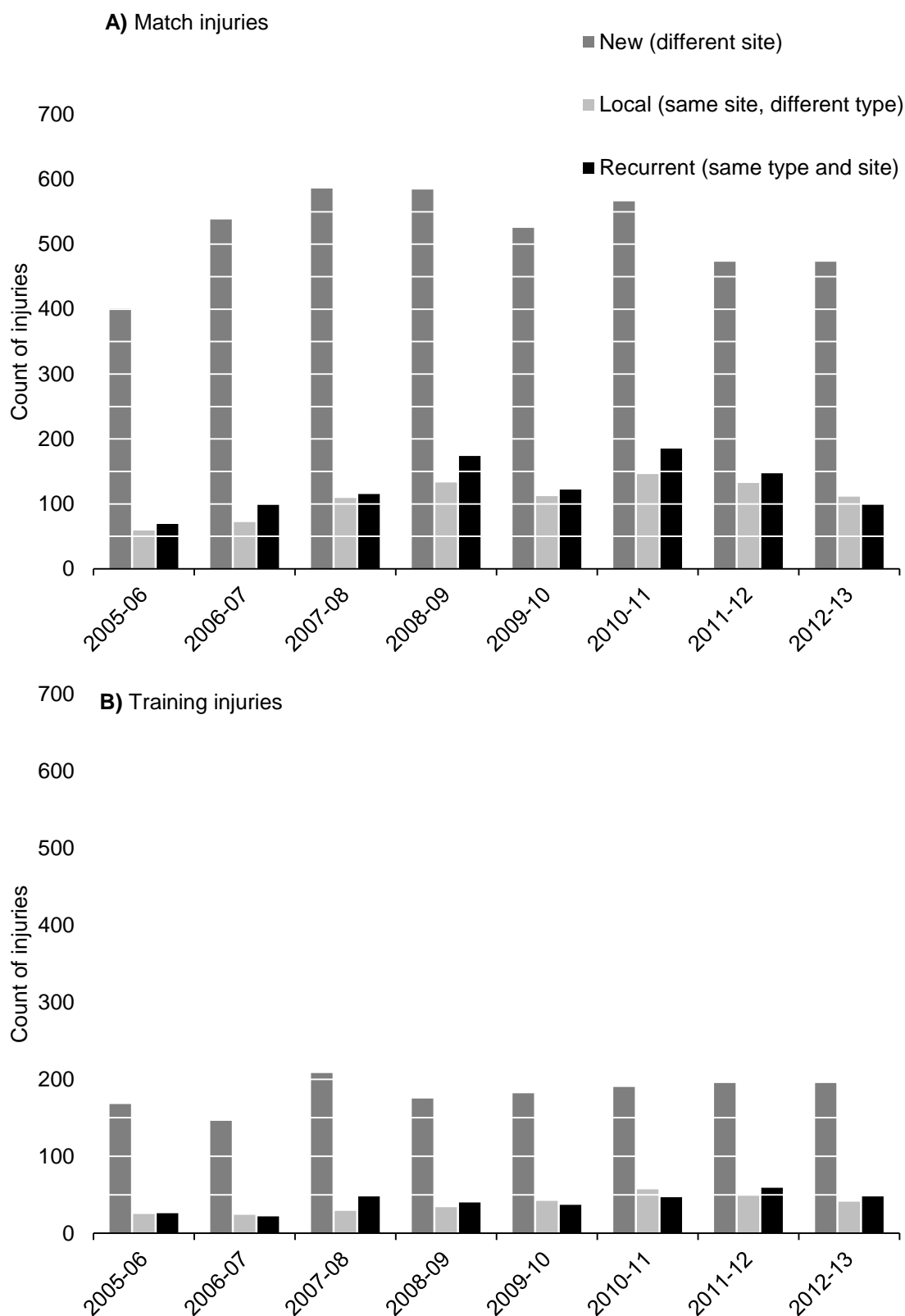


Figure 5.2 Number of subsequent (A) match and (B) training injuries within each Subsequent Injury Definition category (New, different site; Local, same site and different type; Recurrent, same site and type) across the included study seasons.

Table 5.1 displays a descriptive summary of subsequent injuries for players involved in 1-8 seasons of the analysis. Over the eight seasons of the study period, the proportion of subsequent injuries players' sustained that were local or recurrent (rather than new) increased from 21% to 38%. Figure 5.3 displays the injury timelines of the nine players involved in all eight seasons of the study period. Eighty-five percent of players included in the study incurred at least one time-loss injury, with 68% of all players incurring two or more time-loss injuries.

Table 5.1 Descriptive summary of subsequent injuries (New, different site; Local, same site and different type; Recurrent, same site and type) for players involved in 1-8 seasons of the analysis

Number of seasons	Number of players	Mean absence per player, per season [days]	Total number of subsequent injuries per player	Number (%) of injuries per player, according to Subsequent Injury Definition category		
				New (different site)	Local (same site, different type)	Recurrent (same site and type)
1	592	38	1.6	1.2 (79)	0.2 (10)	0.2 (11)
2	333	48	3.5	2.7 (76)	0.3 (10)	0.5 (14)
3	218	49	5.7	4.1 (72)	0.7 (13)	0.8 (15)
4	142	51	8.3	5.8 (70)	1.3 (15)	1.2 (15)
5	111	56	12.8	8.3 (64)	2.0 (16)	2.5 (20)
6	91	59	15.2	9.6 (63)	2.7 (18)	2.9 (19)
7	59	65	20.0	11.8 (59)	3.9 (20)	4.3 (21)
8	9	56	21.0	13.0 (62)	3.7 (17)	4.3 (21)

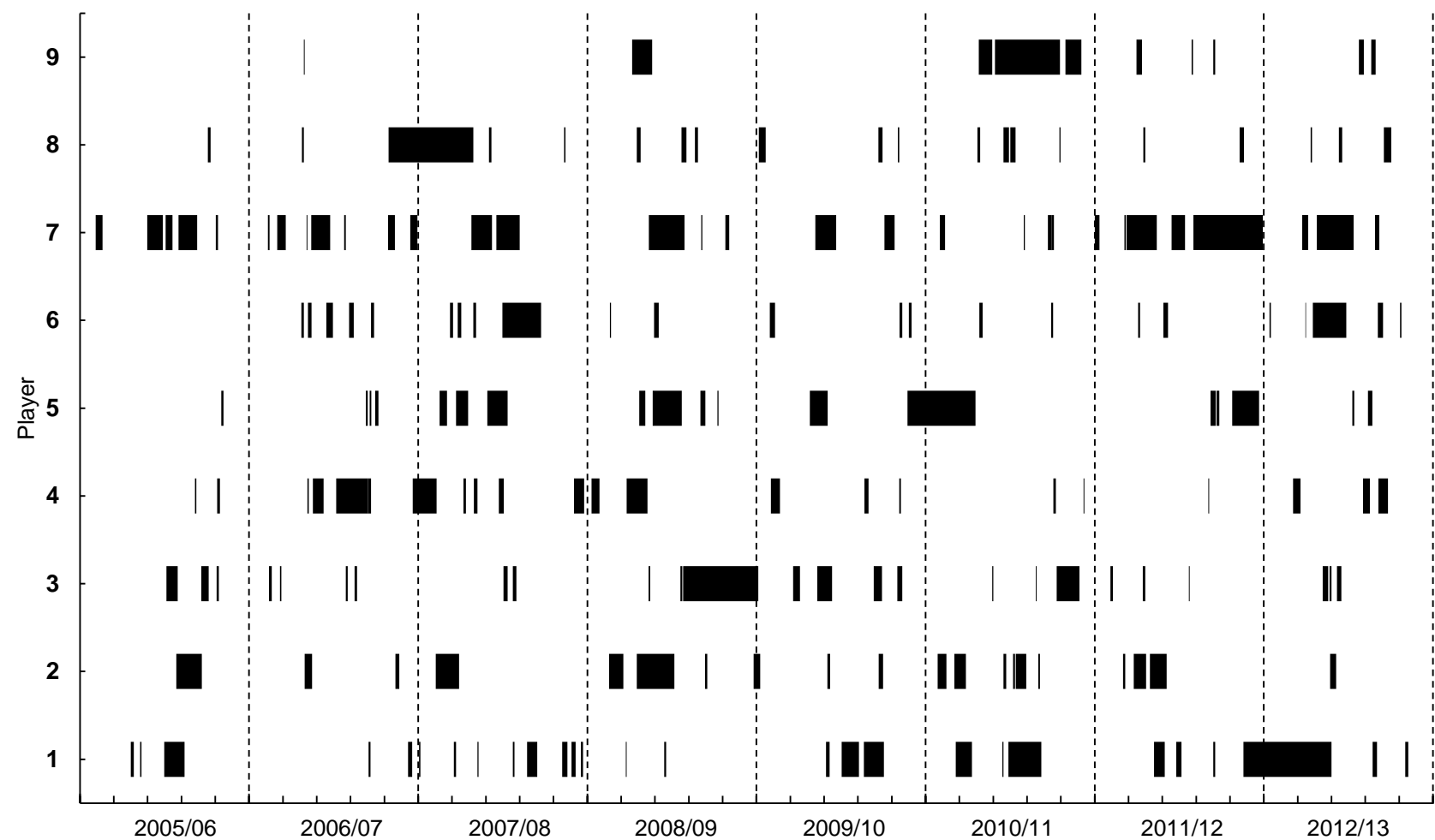


Figure 5.3 Example injury timelines for nine players involved in all eight seasons of the study period. Black area represents a period of absence from full training and/or match-play due to injury.

Figure 5.4 displays the proportion of new, local and recurrent injuries within each injury diagnosis grouping. The five injury diagnosis groupings with the highest proportion of local/recurrent injuries were: (1) Quadriceps muscle injury; (2) Ankle joint capsule sprain; (3) Hamstring muscle injury; (4) Knee cartilage/degenerative injury and (5) Haematoma thigh. Average severity data for each injury diagnosis grouping is presented in the Appendix (Table A.1).

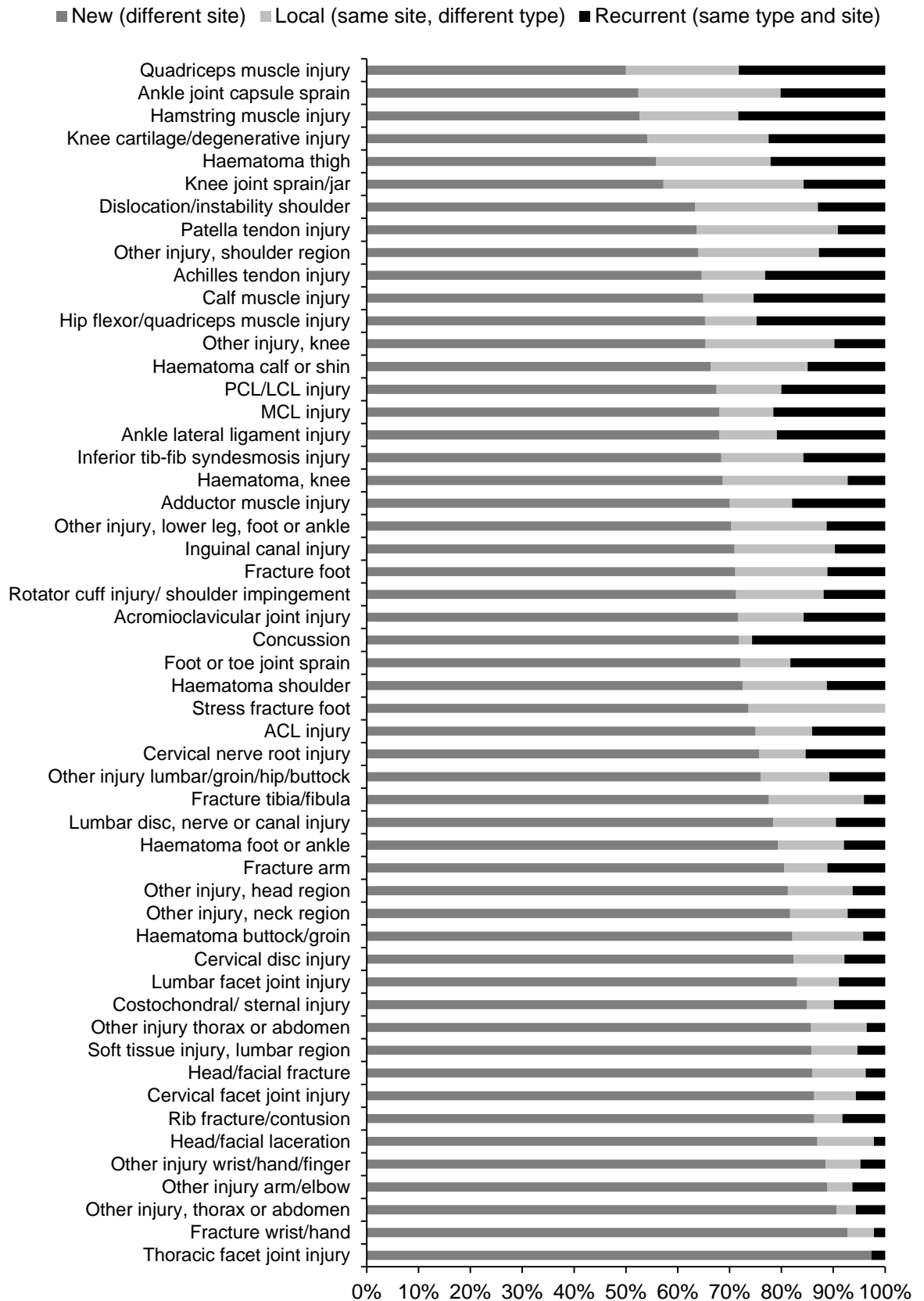


Figure 5.4 Proportion of subsequent injuries (New, different site; Local, same site and different type; Recurrent, same site and type) within each injury diagnosis grouping.

Figure 5.5 shows the frequency patterns of early, late and delayed injuries within each subsequent injury definition category. The majority of new subsequent injuries (93%) were either early or late (i.e. occurred within 12 months of return-to-play from an index injury), whereas a greater proportion of local subsequent injuries (40%) were delayed (i.e. occurred more than 12 months after the index injury). Forty-two percent of recurrent subsequent injuries occurred within two months of return-to-play from an index injury.

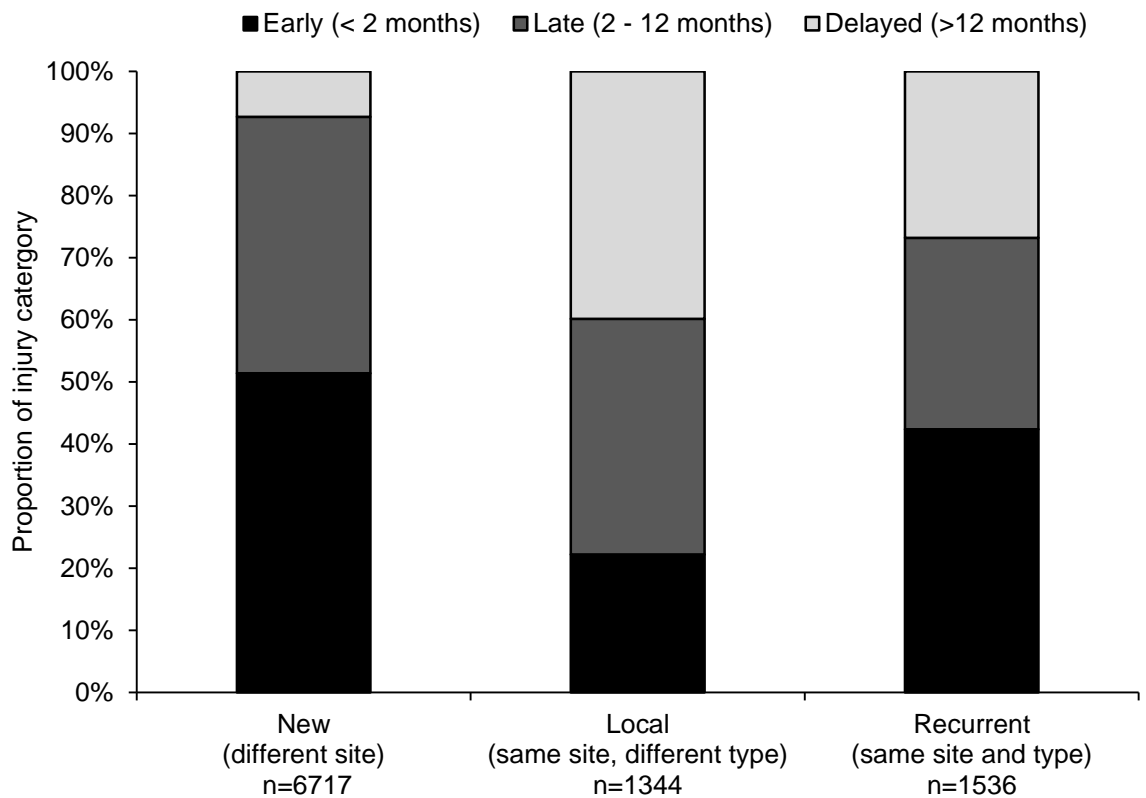


Figure 5.5 Proportion of early (<2 months), late (2-12 months) and delayed (>12 months) injuries within each Subsequent Injury Definition category (New, different site; Local, same site and different type; Recurrent, same site and type).

5.3.2 Subsequent injury severity

There were no substantial differences in the severity of subsequent injuries (new, local or recurrent) in comparison with their related index injury, with all inferences showing ‘very likely’ trivial differences ($\geq 95\%$ likelihood) (Figure 5.6).

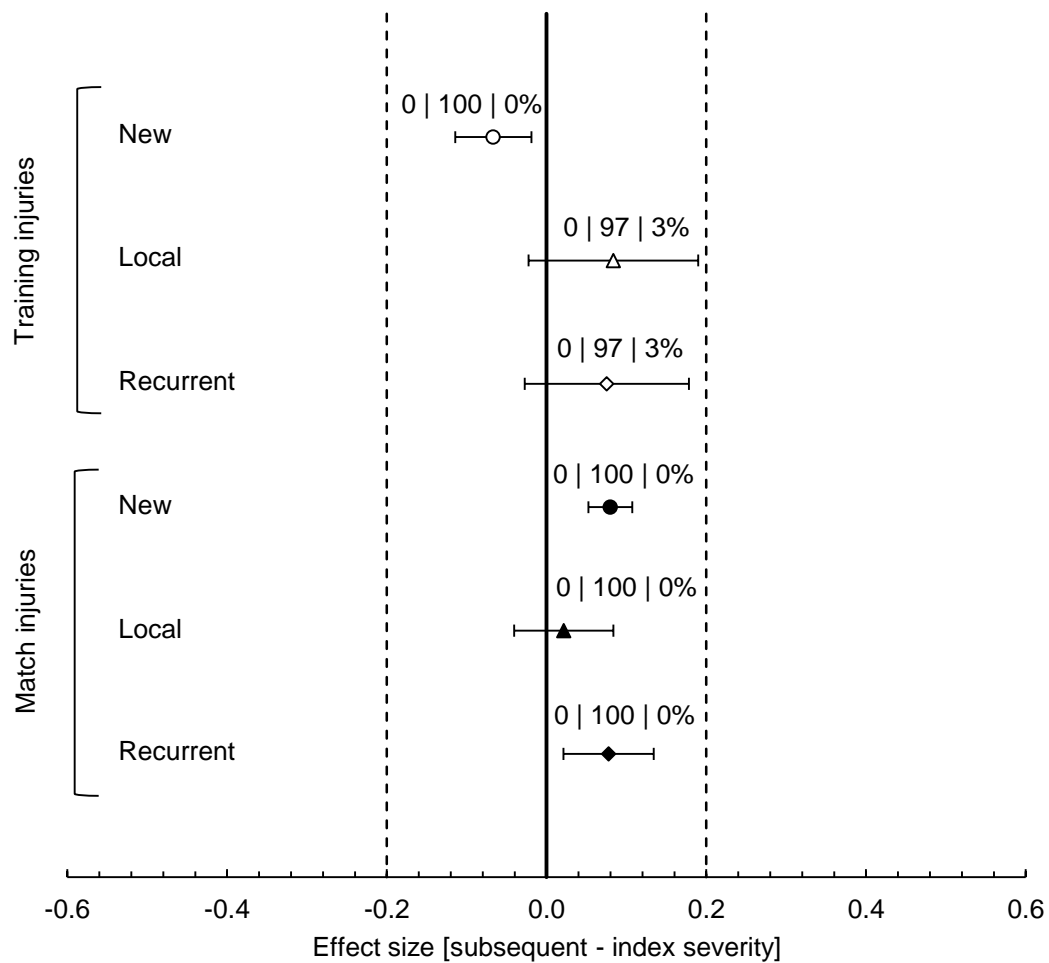


Figure 5.6 Effect sizes (with 90% CI) for differences in the severity of subsequent injuries in comparison with their related index injury (i.e. +’ve effect size indicates subsequent injuries were more severe than their related index), within each Subsequent Injury Definition category (New, different site; Local, same site and different type; Recurrent, same site and type). Data labels give likelihoods that effect is substantially negative | trivial | positive.

5.3.3 Cluster analysis of local and recurrent injuries

The two-step cluster algorithm defined three clusters based on the time to subsequent injury variable, in relation to the time delay between index and subsequent (local and recurrent) injuries. Mean time to subsequent injury in cluster one was 25 ± 22 d, with 88% of injuries classed as ‘early’ and 12% classed as ‘late’ recurrences. Mean time to subsequent injury in cluster two was 143 ± 39 d, with 100% classed as ‘late’ recurrences. Mean time to subsequent injury in cluster three was 557 ± 255 d, with 30% classed as ‘late’ recurrences and 70% classed as ‘delayed’ recurrences. Cluster

one contained 1072 cases (41%), whilst cluster two contained 532 cases (20%) and cluster three contained 1045 cases (39%); the ratio of the largest to smallest cluster sizes was 2.02. The average silhouette coefficient was 0.6 ('Good').

For each injury diagnosis grouping with a sufficient number of cases to allow for normal approximation, the proportion of local and recurrent cases within cluster one (early recurrences) is displayed in Figure 5.7. The overall proportion of local and recurrent subsequent injuries in cluster one was 41%, and so thresholds for substantial beneficial and harmful effects were 31% and 51%, respectively (i.e. $\pm 10\%$). Clear harmful effects (i.e., injuries that had an increased risk of early recurrence) were found for 'other injury, neck region', 'cervical nerve root injury', and 'hip flexor/quadriceps muscle injury', while a possibly harmful effect was found for 'ankle joint capsule sprain' injuries. Clear beneficial effects (i.e., injuries that had a lower risk of early recurrence) were observed for 'haematoma calf or shin', 'MCL injury', 'haematoma thigh', 'dislocation/instability shoulder' and 'ankle lateral ligament injury'.

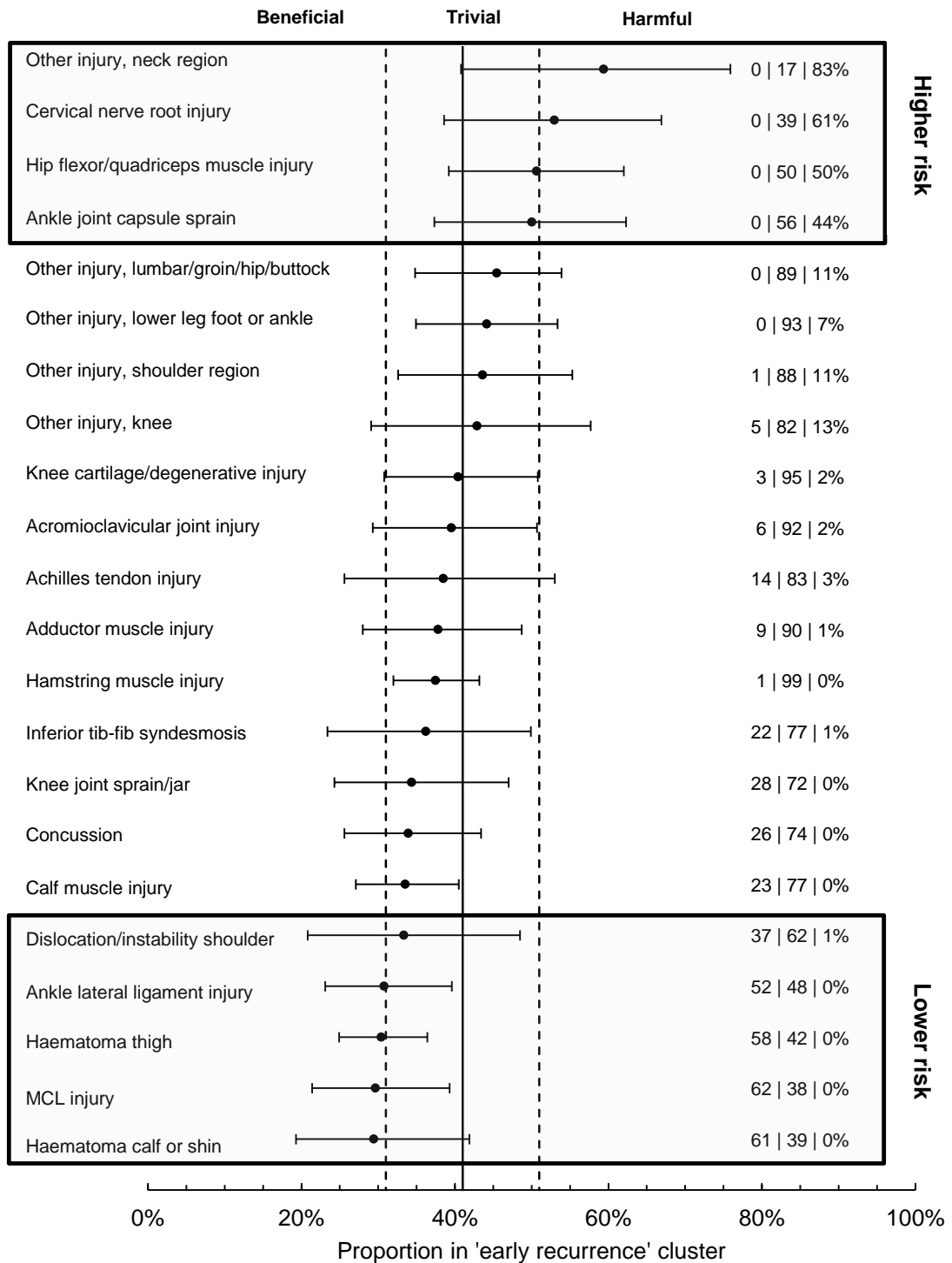


Figure 5.7 Proportion of local and recurrent subsequent injuries in early recurrence cluster for each injury diagnosis grouping, with 90% CIs. Boxes highlight injuries with the highest and lowest risk of early recurrence. Data labels give % likelihood that effect is substantially beneficial | trivial | harmful. Dotted lines represent thresholds for beneficial (31%) and harmful effects (51%), i.e. $\pm 10\%$.

5.4 Discussion

The purpose of the current study was to investigate patterns associated with subsequent injuries within elite Rugby Union players. Subsequent injuries were not more severe than their related index injury. A large proportion of recurrent subsequent injuries (42%) occurred within two months of return-to-play. Specific injury diagnoses that were identified as having a higher risk of early recurrence included: 'other injury, neck region', 'cervical nerve root injury', 'hip flexor/quadriceps muscle injury' and 'ankle joint capsule sprain' injury diagnosis groupings.

Subsequent injuries (new, local and recurrent) were not found to be more severe than the associated index injury of that athlete. This is in contrast to extant literature comparing the severity of recurrent injuries with all other injuries (Chapter 3; Hawkins and Fuller, 1999; Rauh et al., 2007; Waldén et al., 2005); this method of analysis has shown injury recurrences to have substantially higher consequences than new injuries. Therefore, one possible explanation for these findings is that the injuries that are most likely to reoccur are also more likely to be of high severity. However, the injuries identified as having the highest rate of recurrence ('hamstring muscle injury', 'quadriceps muscle injury', 'concussion', 'calf muscle injury', 'hip flexor/quadriceps muscle injury') were not associated with above-average injury severities over the course of the study period (Table A.1). Instead, it may be that athletes who incur more recurrent injuries (e.g. those with high risk taking behaviours) are also more likely to have injuries of greater severity (Hamilton et al., 2011a). This finding highlights the need to include the athlete as a random effect variable within statistical models, in order to account for the heterogeneity in injury risk across a population (Hamilton et al., 2011a). Such models will be utilised within Chapter 7 of this thesis.

A large proportion of recurrent subsequent injuries (42%) recorded in the current study occurred within two months of return-to-play from an index injury. In elite football (soccer) the majority of recurrences (78-93%) have also been reported to occur within two months of return-to-play (Häggglund et al., 2007; Häggglund et al., 2009a; Häggglund et al., 2009b). One reason for the differences between these rates may be the congested fixture periods (i.e. >2 matches per week) that are common to

professional football (but not Rugby Union), which may increase the likelihood that players return-to-play prematurely (Ekstrand et al., 2004a). Nonetheless, the high proportion of early recurrences within both of these elite sports is of concern, and stresses the importance of ensuring complete and effective rehabilitation of injured players before return-to-play. Inadequate rehabilitation is likely to increase the risk for re-injury due to incomplete healing of the affected tissue, and/or because full motor skill and fitness properties have not been restored (Hägglund et al., 2007). The use of a multi-component assessment strategy in professional Rugby League (based on comparing clinical and functional strength defects in the injured limb to the non-injured limb) was reported to be useful in guiding the health team's decision regarding return-to-play (Brown and Brughelli, 2014). While standardised return-to-play assessment procedures of this nature are likely to be commonplace within elite Rugby Union, no studies have been published to describe their use. The return-to-play decision is a complex process that typically involves external pressure from a number of groups that stand to benefit from a player's timely return to match-play (e.g. players, coaches, fans, media, sponsors) (Creighton et al., 2010). As such, in an elite sport setting the return-to-play decision will most likely be one of risk management rather than risk elimination (Orchard and Best, 2002). The use of machine-learning models for predicting return-to-play (Chapter 8), alongside evidence-based standardised return-to-play assessment procedures, may help to clarify this decision making process. Furthermore, highlighting the negative relationship between injury burden and team success (Chapter 4) may help emphasise the overall importance of preventing both new and subsequent injuries.

Four injury diagnoses were identified as having an increased risk of early recurrence, namely 'other injury, neck region', 'cervical nerve root injury', 'hip flexor/quadriceps muscle injury' and 'ankle joint capsule sprain' injury diagnosis groupings. Further consideration of treatment and rehabilitation protocols for these injury diagnoses may therefore be required. Of note, injuries relating to the neck and cervical spine had the highest risk for early recurrence. Given the potential (albeit low absolute risk) for permanent disability occurring as a result of injuries to these regions (Quarrie et al., 2002), alongside the risk of premature degenerative disease of the cervical spine in front-row forwards (Trewartha et al., 2014), a cautious approach to rehabilitation from index injuries to the neck region should be encouraged.

Specifically, the typical absence observed during the study period for ‘cervical nerve root injury’ and ‘other injury, neck region’ injuries (median absence = 8 d and 5 d, respectively) may need to be increased in order to reduce the likelihood of an early injury recurrence to the neck region.

Interestingly, whilst a higher risk of early recurrence existed for ankle joint capsule sprain injuries, a lower level of early recurrence risk was found for ankle lateral ligament injuries. This finding suggests that while well-established treatment and preventative measures for ankle lateral ligament sprains, such as proprioceptive training (Mohammadi, 2007), prophylactic ankle bracing (Sharpe et al., 1997) and objective measurements of the player’s recovery and functional status (Anderson, 2002) appear to be effective in preventing the early recurrence of ankle lateral ligament sprains, they may not be as efficacious for ankle joint capsule sprains. It may be that due to their anatomical position, ankle joint capsule sprains are more difficult to assess in comparison with ankle lateral ligament sprains, which may increase the likelihood that a player returns to participation prematurely. As shown in Figure 5.4, a substantial proportion of ankle joint capsule sprains (23%, n=36) were classified as local injuries (i.e., the player had incurred a previous ankle injury) and the majority of these (67%, n=24) were subsequent to ankle lateral ligament injuries. Following ankle lateral ligament injuries, structural damage commonly occurs not only to the ligamentous tissue, but also to the nervous and musculotendinous tissue surrounding the ankle complex (Hertel, 2000). As such, increased joint laxity resulting from the ligament injury is combined with neuromuscular deficits, and the resultant effects (e.g. reduced joint position sense, slower firing of peroneal muscles, impaired balance, strength deficits etc.) may explain the increased risk of early re-injury of the ankle joint capsule (Hertel, 2000). Therefore, during the treatment and rehabilitation of ankle lateral ligament injuries, the restoration of both neuromuscular function and mechanical stability should be completed before return-to-play, in order to prevent early re-injury in the form of ankle joint capsule sprains.

For hip flexor/quadriceps muscle injuries, there is no clear consensus on assessing readiness for return-to-play (Orchard and Best, 2002), although a return to full range of motion, strength and functional activities is perhaps the most common and safe

approach (Heiser et al., 1984). In an elite sport setting, magnetic resonance imaging (MRI) may also be used to guide return-to-play decisions for quadriceps muscle injuries. Cross et al. (2004) used MRI examinations from acute quadriceps muscle strains in professional Australian Rules football players, and reported that rectus femoris-central tendon strains were associated with significantly longer return-to-play times (mean = 27 days) than strains in the periphery (mean = 9 days) or vastus muscles (mean = 4 days). As such, MRI examinations can be used to estimate the likely rehabilitation period for a hip flexor/quadriceps muscle injury, as well as confirming that the tissue has healed sufficiently.

Concussion is the one of the most common match injuries within professional Rugby Union (Kemp et al., 2013), and is currently a prominent and contentious issue within many contact sports (Helmy et al., 2013). A relatively high proportion of all subsequent concussion injuries were recurrences (26%); given the reported association between previous concussions and increased likelihood of future concussive injuries (Guskiewicz et al., 2003), as well as overall injury risk (Nordstrom et al., 2014), players with a history of concussion injuries should be managed prudently. Of particular concern may be the risk of ‘second impact syndrome’, whereby an athlete sustains a second head injury before the symptoms associated with the first have fully cleared. The effects of such events may be catastrophic, although strong scientific evidence to support the ‘second impact’ concept is currently lacking (McCrory et al., 2012). Approximately a quarter of all concussion recurrences reported within the current study period occurred within two months of the player returning to participation from a previous concussive incident (i.e. ‘early recurrence’). This finding highlights the importance of current studies focusing upon the optimal recognition, management and return-to-play practices for players with concussion injuries (e.g. Fuller et al., 2014). Currently, a graduated return-to-play protocol exists, which enables players to return within one week if they remain asymptomatic at each level of the process (McCrory et al., 2013). In light of the presented findings and concerns regarding the potential effects of ‘second impact syndrome’, the minimal stand-down period for concussion injuries should be increased.

As would be expected, those players involved in a higher number of study seasons incurred a larger proportion of local and recurrent subsequent injuries, and a smaller proportion of new subsequent injuries, compared with less experienced players (Table 5.1). As a player's career progresses and their 'injury history' accumulates, the likelihood of them incurring an injury to a previously injured body site increases. The effect of these 'previous injury loads' on current injury risk will be examined in Chapter 7.

The 'early', 'late' and 'delayed' definitions for recurrent injuries outlined in the consensus statement for Rugby Union (Fuller et al., 2007c) were supported by the two-step cluster algorithm. This finding lends quantitative support to the use of these groupings.

Local injuries can be identified easily and accurately within injury surveillance projects, and will help to elucidate the role that previous occurrences have upon future injury risk. An injury to a given site may predispose an athlete to another injury at that site through a myriad of mechanisms (e.g. altered proprioception or strength); such injuries are of concern, regardless of whether the subsequent injury is of the exact same type as the index occurrence (Hamilton et al., 2011a). When analysing sport injury data, future studies should therefore classify local injuries alongside injury recurrences of the same type and site, as such data will be helpful in identifying causal links and shaping future preventative efforts.

A limitation of the present study was that cases in which players returned from injury towards the end of a given season would have a reduced likelihood of incurring an 'early' subsequent injury (due to the off-season), which may have biased the results. Additionally, players likely incurred injuries prior to (or outside of) their inclusion in the study, through rugby participation for other clubs or in other competitions beyond the capture remit of the England Professional Rugby Injury Surveillance Project, which may have resulted in the misclassification of some cases. A further limitation of the present study was the possibility of an inflated Type I error rate (an increase in the chance of declaring a marginally harmful effect beneficial) due to the multiple comparisons that were undertaken. Whilst such an inflation in error rate is possible, the usual remedy of making tests more conservative has been declared inappropriate by several authors (e.g. Hopkins et al., 2009a; Perneger, 1998). For

instance, such adjustments cause inflation in the Type II error rate, and the interpretation of a finding becomes dependent on the number of other tests performed. Instead, it is recommended that raw confidence intervals be presented alongside acknowledgment of the potential for such inflated errors, so that readers may make their own informal decision regarding the plausibility of a reported effect (Rothman, 1990).

5.4.1 Conclusion

The present study aimed to describe the distribution and severity of subsequent injuries across a cohort of elite Rugby Union players. Subsequent injuries were not more severe than their associated index injury. A large proportion of recurrent injuries (42%) occurred within two months of return-to-play, with specific injury diagnoses identified as having a higher risk of early recurrence. These findings may be used to drive targeted secondary prevention efforts, such as reconsideration of treatment, rehabilitation and return-to-play protocols for ankle lateral ligament injuries (to avoid early re-injury to the ankle joint capsule), hip flexor/quadriceps strains, and injuries related to the neck region.

CHAPTER SIX

The Influence of an Artificial Playing Surface on Injury Risk and Perceptions of Muscle Soreness in Elite Rugby Union Players

6.1 Introduction

There is a growing interest in the use of artificial turf surfaces in Rugby Union. In particular, artificial surfaces may be a useful means of increasing participation in the sport by allowing greater usage of a given pitch, especially in regions where natural turf pitches are difficult to maintain. Indeed, the International Rugby Board (2008) has published “Regulation 22: Standard relating to the use of artificial playing surfaces”. During the 2012/13 season, an English Premiership team became the first elite professional Rugby Union team to install and play matches on an artificial surface. Given the purported benefits of artificial turf over natural grass, such as its ability to permit greater usage, lower maintenance costs and its ‘all weather’ capability, it is expected that their use by teams across all levels of the game will increase in the future.

Many injuries common to Rugby Union may be influenced by the shoe surface interaction, the parameters of which are likely to differ between various types of playing surface (Drakos et al., 2013). The playing surface may also have an indirect influence on injury risk by changing the nature of the game (e.g. running speeds, ball-in-play time and concomitant fatigue levels), as has been reported in other sports (Andersson et al., 2008; Di Michele et al., 2009; Gains et al., 2010; Norton et al., 2001). Whilst overall acute injury risk on new generation artificial surfaces in elite football appears to be equivalent to natural grass (Bjørneboe et al., 2010; Ekstrand et al., 2006), the influence of an artificial playing surface on injury risk in elite Rugby Union is currently unclear. Fuller et al. (2010b) conducted a two-season investigation comparing match injuries sustained on artificial turf and natural grass by Rugby Union teams competing in Hong Kong’s Division 1. The authors reported no significant difference in the incidence rate of match injuries between the two surfaces. The number of anterior cruciate ligament injuries in matches was notably higher on artificial turf (n=5) compared with natural grass (n=1), but this difference was not statistically significant. However, the study population used from the Hong

Kong Division 1 is unlikely to be comparable with that of English Premiership teams, as evidenced by the significant differences in anthropometrics and match injury incidence rates between the two populations (Fuller et al., 2010b), and so the results may not be applicable to elite Rugby Union cohorts.

Wounds, burns and friction injuries were reported to be more common on older generations of artificial turfs compared with natural grass (Ekstrand and Nigg, 1989; Gaulrapp et al., 1999). More recently, Ekstrand et al. (2011) reported that such injuries might no longer be a problem when playing football on modern high quality artificial turf pitches. However, skin injuries are likely to be underreported in studies that use time-loss injury definitions (Ekstrand et al., 2006). Moreover, the risk of incurring such acute skin injuries may be higher during Rugby Union matches in comparison with football due to the frequent player-surface interactions, but this is yet to be investigated. Burillo et al. (2012) investigated perceptions of football users (players, coaches and referees) towards third-generation artificial surfaces, and reported that skin abrasions were seen as the biggest disadvantage of artificial turf. Whilst surface-related skin damage injuries are typically minor, they can be problematic if they cover a large area or when foreign materials become embedded in the skin lesion, and the related discomfort may negatively impact on players' performances (Peppelman et al., 2013). As such, there is a need to understand the influence that artificial surfaces have upon the incidence and nature of abrasion injuries during elite Rugby Union matches, in order to help develop abrasion-related injury prevention strategies and attenuate players' negative perceptions (Twomey et al., 2014).

Professional soccer players have reported greater muscle and joint soreness and longer recovery times following matches played on new generation artificial turf (Poulos et al., 2014). An important component in the management of team-sport athletes is the understanding of how players respond to and recover from matches ahead of the subsequent week's training and match demands (Montgomery and Hopkins, 2012). Thus, an understanding of the influence that an artificial playing surface has upon perceptions of muscle soreness in this cohort is required.

In light of the dearth of evidence concerning the effects of artificial playing surfaces on injury risk in elite Rugby Union, and concerns regarding their impact upon

abrasion injury risk and muscle soreness, this study was commissioned by the RFU, Premiership Rugby and Rugby Players Association to investigate these topics as an extension of the Professional Rugby Injury Surveillance Project. Overall, this study sought to investigate the influence that a third-generation artificial playing surface has upon time-loss and abrasion injury risk, and perceptions of muscle soreness in elite Rugby Union players.

6.2 Methods

6.2.1 Study design and setting

This was a prospective cohort study of injuries (time-loss and abrasion) and perceptions of muscle soreness following Premiership and National Cup fixtures involving one English Premiership team. The team's home fixtures were played on an artificial turf surface, whilst their away fixtures (on natural grass surfaces) were used for comparison. Data pertaining to both the home and away team were included in the dataset. A pilot study was conducted during the second half of the 2012/13 season (13 matches) to test the appropriateness of the time-loss and abrasion injury data collection methods. A season-long data collection period was then conducted throughout the 2013/14 season (27 matches). Time-loss injury data (collected as part of the Professional Rugby Injury Surveillance Project) from both these periods were included in the analysis to maximise statistical power. For abrasion injuries and perceptions of muscle soreness, only data collected throughout the 2013/14 season were included in the analysis.

The study design and data collection procedures were approved by the Research Ethics Approval Committee for Health at the University of Bath. Written informed consent was obtained from all players included in the study, and all data were anonymised. The third-generation sand and rubber filled artificial surface (SIS Rugger 65 mm, Support in Sport, Cumbria) was tested independently to ensure it complied with RFU standards, specifically IRB regulation 22. Both laboratory and field tests were conducted to assess the suitability of the artificial surface for Rugby Union in relation to three categories (International Rugby Board 2010): (1) Ball-surface interaction; (2) Player-surface interaction and (3) Durability.

6.2.2 Variables

The definitions and procedures used in this study were consistent with the international consensus statement for epidemiological studies in Rugby Union (Fuller et al., 2007c). The primary (time-loss) injury definition used in this study was:

‘Any physical complaint sustained by a player during a first-team match that prevented the player from taking a full part in all training activities typically planned for that day, and/or match play for more than 24 hours from midnight at the end of the day the injury was sustained’.

All injuries were recorded by medical personnel at each club using a modified Orchard Sports Injury Classification System (OSICS) (Orchard, 1995) and standard injury report form. Individual match and grouped training exposure data were reported weekly by strength and conditioning staff using a standard training report form.

Additionally, the incidence and nature of all abrasion injuries incurred (regardless of any resultant time-loss) were assessed within 60 min of the completion of each match by an assigned field researcher from the University of Bath. Abrasions were defined as excoriations of the skin produced by acute contact with the playing surface, and were identified by club medical personnel or the assigned research officer. Information pertaining to the size, depth, location and pain induced by each abrasion was recorded. Players were asked to give a subjective rating of pain relating to the abrasion injury on a six point scale, in which ‘0’ represented no pain, ‘1’ represented minor pain, ‘3’ represented moderate pain and ‘5’ represented severe pain. The depth of the abrasion was also graded; a ‘first-degree’ abrasion involved damage to the epidermis only, a ‘second-degree’ abrasion involved the epidermis and dermis (and may have induced punctate bleeding and tissue exudate), while a ‘third-degree’ abrasion involved damage to the subcutaneous layer. An abrasion was recorded as an ‘exacerbation’ for cases in which a player reported a worsening in the condition of an index abrasion that had not fully healed. These cases were verified against past recorded abrasion records and/or with medical personnel.

Muscle soreness responses were reported by a sample of opposition players (i.e., non-Saracens players) on each of the four days following one match played on the artificial turf surface, as well as one match played on a natural grass surface for comparison. Muscle soreness responses were collected over two consecutive weeks in order to avoid bias relating to the timing of the fixture within the season. The sample was balanced, such that a similar number of players responded having played on the artificial surface first (n=50) as those who played on a natural grass surface

first (n=45). On each of the four days following a selected match, players were sent a Short Message Service (SMS) message to which they responded with a number indicating their level of general muscle soreness. Data for players who played less than 30 minutes and/or provided fewer than three comparable responses were excluded from the analysis. The question sent to players was:

‘Please indicate your level of muscle soreness by replying with a number between 0-5, where 0 signifies ‘no soreness’, 3 signifies ‘a light pain when walking up or down stairs’ and 5 signifies ‘a severe pain that limits my ability to move’.

6.2.3 Statistical methods

Incidence rates were recorded as the number of injuries per 1000 player hours of match exposure. Player match exposures were calculated on a team basis, assuming that each team game involved 15 players and lasted for 80 min. Severity was determined by the number of days absence from training or match play. Non-parametric tests were used to compare the severity of injuries, where appropriate. Injury burden was calculated by multiplying injury incidence rate by mean injury severity. Magnitude-based inferences were used to provide an interpretation of the real-world relevance of the outcome, based directly on uncertainty in the true value of the effect statistic in relation to a smallest worthwhile effect (Batterham and Hopkins, 2006). The smallest worthwhile effect for time-loss injuries was an incidence rate ratio of 1.43 (moderate effect), while for abrasion injuries (which were expected to be more common and less severe) a threshold of 2.00 (large effect) was used (Hopkins, 2010), using injuries incurred on natural grass as the reference category. A Pearson correlation coefficient was used to assess the relationship between the weekly rainfall prior to the match and the number of abrasions incurred on the artificial turf.

All estimations pertaining to muscle soreness responses were made using the *nlme* package (Pinheiro et al., 2014) in R (version 3.03, R Foundation for Statistical Computing, Vienna, Austria). A linear mixed model was used, with each measure of soreness analysed separately as the dependent variable. Data were processed such that each observation had values representing the identity of the player (95 levels), the number of days since the match (4 levels, represented by integer values of 1-4),

and the playing surface (2 levels, natural grass or artificial turf). The fixed effects in the model were the playing surface, the number of days post-match, and an interaction between surface and days post-match. To model the repeated measurements within players, a random effect was included that allowed the effect of time to vary across players. A first-order autoregressive covariance structure was used, such that data points close in time were assumed to be more highly correlated than data points distant in time. Akaike's Information Criterion (AIC) and the -2 Log Likelihood were used to assess and compare the model's goodness of fit. Magnitudes of effects were evaluated using standardization. Specifically, the between-player SD (representing the typical variation in soreness between players on any given day) was derived from the mixed effects model; effects were divided by this SD and their magnitudes interpreted with the following scale: <0.2, trivial; 0.2 to 0.6, small; 0.6 to 1.2 moderate and >1.2, large (Hopkins et al., 2009a). Effects were classified as unclear if the $\pm 90\%$ confidence limits crossed thresholds for substantial positive and negative values (± 0.2 standardised units) by $\geq 5\%$, otherwise the effect was deemed clear.

The minimum sample size required to detect an incidence rate ratio (IRR) of ≥ 1.43 (Hopkins, 2010) with 80% power and a 90% confidence level was estimated to be 1107 player hours on both surfaces, or 28 equivalent matches on each surface (Kirkwood and Sterne, 2003).

6.3 Results

6.3.1 Incidence rates, severity, and burden of time-loss injuries

Table 6.1 displays the exposure time recorded for each pitch type within each category of injury. Of the included matches relating to time-loss injuries, 34 were Premiership fixtures and 7 were National Cup fixtures (opposition data were not collected in three of these fixtures as they were outside of the capture remit of the England Professional Rugby Injury Surveillance Project). For data relating to abrasion injuries, 23 were Premiership fixtures and 4 were National Cup fixtures.

Table 6.1 Player exposure times [h] recorded for each category of injury

	Time-loss injury player hours (number of equivalent matches)	Abrasion injury player hours (number of equivalent matches)
Artificial turf	760 (19)	480 (12)
Natural grass	820 (20.5)	600 (15)
Total	1580 (39.5)	1080 (27)

A total of 110 match time-loss injuries (artificial, 50; natural, 60) were reported during the study period. This equated to an injury incidence rate on artificial turf of 66 per 1000 player hours (90% CI, 52-83), and an incidence rate on natural grass of 73 per 1000 player hours (90% CI, 59-90). The incidence rate ratio, using natural grass as the reference category, was 0.90 (90% CI, 0.66-1.23); there was a 90% likelihood that the difference in injury incidence rates between playing surfaces was trivial (Figure 6.1).

Table 6.2 displays the mean and median injury severity observed on each playing surface. There was no clear difference in the mean severity of injuries sustained on the two playing surfaces. The median severity of injuries sustained on natural grass was higher than on artificial turf, although this difference was not statistically significant ($P=0.09$). This difference is likely explained by the higher incidence rate of minor injuries, and lower incidence rate of moderate injuries, sustained on the artificial turf (Table 6.3).

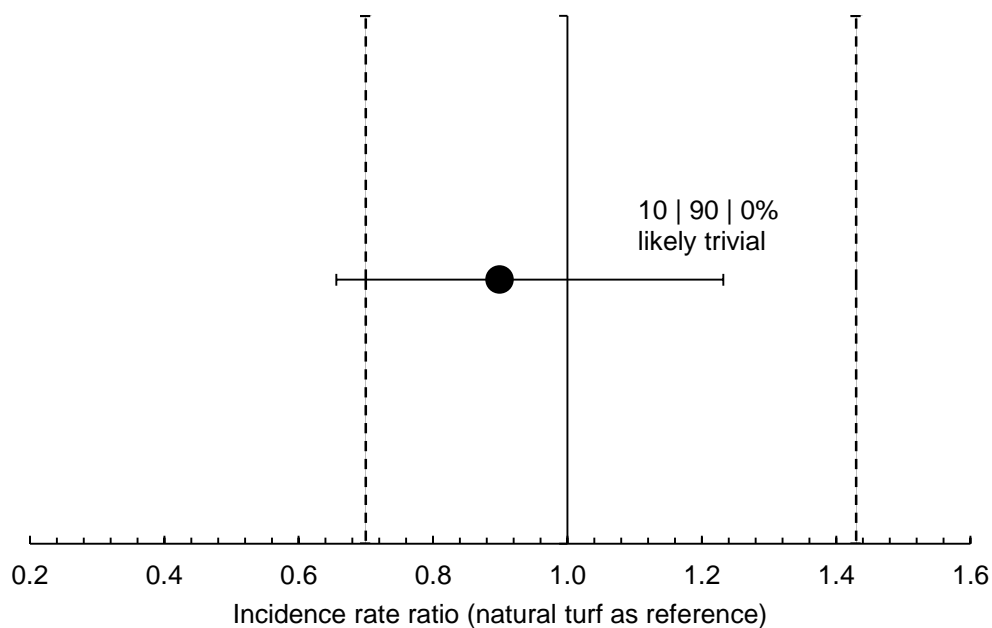


Figure 6.1 Incidence rate ratio (with 90% CI) of time-loss injuries, using natural grass as the reference group. Dotted lines represent thresholds for smallest worthwhile difference (0.70 and 1.43). Data labels give % likelihood that the effect is beneficial | trivial | harmful.

Table 6.2 Severity of time-loss injuries [days] sustained on artificial turf and natural grass

	Mean \pm 90% CL	Observed SD	Median \pm 90% CL
Artificial turf	20.7 \pm 8.2	34.5	6.5 \pm 2.0
Natural grass	18.5 \pm 9.8	23.0	11.5 \pm 3.0

Table 6.3 Incidence rate of time-loss injuries [injuries per 1000 player h] on artificial turf and natural grass as a function of injury severity, with rate ratio (using natural grass as reference) and inference regarding the magnitude of difference

	Artificial turf (90% CI)	Natural grass (90% CI)	Rate ratio (90% CI)	Inference
Minor (2-7 days)	34.2 (24.8-47.2)	21.4 (14.5-31.6)	1.6 (1.0-2.7)	Artificial possibly >
Moderate (8-21 days)	17.1 (10.8-27.0)	34.5 (25.4-46.9)	0.5 (0.3-0.9)	Artificial likely <
Severe (> 21 days)	14.5 (8.8-23.8)	15.5 (9.8-24.4)	0.9 (0.5-1.8)	Unclear

The injury burden for matches played on the artificial surface was 1362 days per 1000 player h (90% CI: 1079-1719), and for matches played on natural grass the injury burden was 1355 days per 1000 player h (90% CI: 1096-1675). The incidence rate ratio, using natural grass as the reference category, was 1.01 (90% CI, 0.73-1.38); there was a 94% likelihood that the difference in injury burden between playing surfaces was trivial (Figure 6.2).

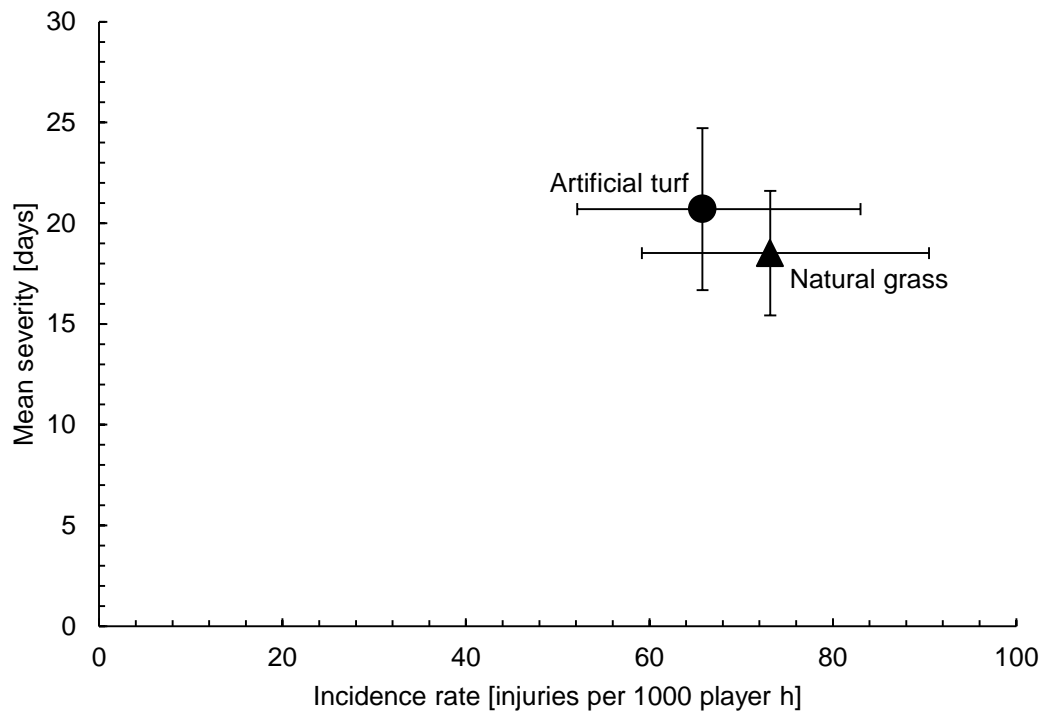


Figure 6.2 Injury incidence rate and severity for time-loss injuries incurred on artificial turf and natural grass. Vertical and horizontal bars represent 90% CIs for severity and incidence rate, respectively.

6.3.2 Injury event

The most common injury event on both surfaces was being tackled (Table 6.4). The incidence rate of injuries incurred through unknown events was also possibly higher on the artificial turf, whilst the incidence rate of injuries incurred during running was possibly lower on the artificial turf. The incidence rate of injuries sustained in the scrum was higher on the artificial turf (n=5) compared with natural grass (n=2), although this effect was not clear. All five of the scrum injuries incurred on the artificial surface were recorded during the 2012/13 pilot study period, with none recorded during the 2013/14 season. Once again, the small numbers negate any firm conclusions regarding these events.

Table 6.4 Incidence rate of time-loss injuries [injuries per 1000 player h] on artificial turf and natural grass as a function of inciting event, with rate ratio (using natural grass as reference) and inference regarding the magnitude of difference

Injury event	Artificial turf (90% CI)	Natural grass (90% CI)	Rate ratio (90% CI)	Inference
Collision (accidental)	5.3 (2.3-12.0)	8.3 (4.5-15.5)	0.6 (0.2-1.8)	Unclear
Collision (non accidental)	1.3 (0.3-6.8)	2.4 (0.7-7.6)	0.5 (0.1-3.9)	Unclear
Contact with ground	2.6 (0.8-8.4)	-	-	Unclear
First set scrum [†]	12.3 (5.9-25.7)	4.6 (1.4-14.6)	2.7 (0.7-10.7)	Unclear
Lineout [†]	2.5 (0.5-12.8)	2.3 (0.4-11.8)	1.1 (0.1-11.3)	Unclear
Maul	-	1.2 (0.2-6.2)	-	Unclear
Ruck	3.9 (1.5-10.2)	6.0 (2.9-12.4)	0.7 (0.2-2.2)	Unclear
Running	5.3 (2.3-12.0)	10.7 (6.2-18.5)	0.5 (0.2-1.3)	Artificial possible <
Tackled	15.8 (9.8-25.4)	20.2 (13.6-30.2)	0.8 (0.4-1.5)	Unclear
Tackling	10.5 (5.9-18.8)	11.9 (7.1-20.0)	0.9 (0.4-1.9)	Unclear
Unknown	13.2 (7.8-22.1)	7.1 (3.6-14.0)	1.9 (0.8-4.4)	Artificial possibly >

[†]Only forwards were considered to be 'at risk' during these events.

6.3.3 Nature of injury

There were no clear differences in the location or type of injuries sustained on the two playing surfaces (Table 6.5). The most common injury location on both surfaces was the lower limb, and the most common injury types were minor joint traumas and neural conditions. More ‘avulsion or chip fracture injuries’ were sustained on natural grass (n=5) than on artificial turf (n=0), although the small numbers negate any clear conclusions regarding this difference.

Table 6.5 Incidence rate of time-loss injuries [injuries per 1000 player h] on artificial turf and natural grass as a function of injury location and type

Injury	Incidence rate of match injuries	
	Artificial turf	Natural turf
<i>Location</i>		
Head and neck	13.2 (7.8-22.1)	17.9 (11.7-27.3)
Lower limb	36.8 (27-50.3)	34.5 (25.4-46.9)
Trunk	2.6 (0.8-8.4)	6.0 (2.9-12.4)
Upper limb	11.8 (6.8-20.5)	13.1 (8-21.5)
<i>Type</i>		
Articular/chondral damage	1.3 (0.3-6.8)	3.6 (1.4-9.2)
Avulsion or chip fracture	-	6.0 (2.9-12.4)
Complete rupture of tendon	1.3 (0.3-6.8)	-
Dislocation	-	2.4 (0.7-7.6)
Fracture (Not stress or avulsion)	-	3.6 (1.4-9.2)
Haematoma/bruising/cork	6.6 (3.2-13.7)	7.1 (3.6-14)
Laceration/skin condition	2.6 (0.8-8.4)	-
Ligament tear or sprain	5.3 (2.3-12)	3.6 (1.4-9.2)
Minor joint trauma +/- synovitis	14.5 (8.8-23.8)	17.9 (11.7-27.3)
Muscle tear or strain	7.9 (4-15.5)	10.7 (6.2-18.5)
Muscle spasm/cramps/soreness/trigger points/myalgia/overuse	3.9 (1.5-10.2)	-
Neural condition/nerve damage	13.2 (7.8-22.1)	16.7 (10.7-25.9)
Recurrent instability/subluxation	1.3 (0.3-6.8)	-
Stress fracture	2.6 (0.8-8.4)	-
Tendonitis/bursitis/enthesopathy/apophysitis/periostitis	2.6 (0.8-8.4)	-

6.3.4 Abrasion injuries

A total of 66 abrasion injuries (artificial, 57; natural, 9) were reported during the 2013/14 season. This equated to an injury incidence rate of 119 per 1000 player hours (90% CI, 96-148) on artificial turf, and an incidence rate of 15 per 1000 player hours (90% CI, 9-26) on natural grass. The incidence rate ratio, using natural grass as the reference category, was 7.92 (90% CI, 4.39-14.28); there was a 100% likelihood that the incidence rate of abrasion injuries on artificial turf was substantially higher than on natural grass (Figure 6.3).

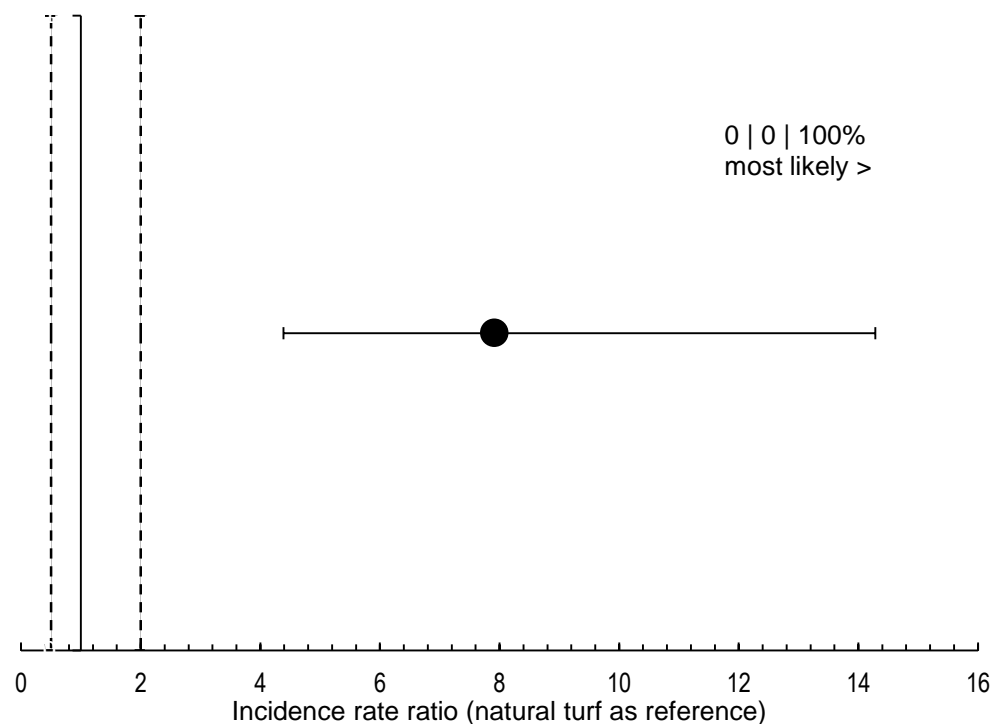


Figure 6.3 Incidence rate ratio (with 90% CI) of abrasion injuries, using natural grass as the reference group. Dotted lines represent thresholds for smallest worthwhile difference (0.5 and 2.0). Data labels give % likelihood that the effect is beneficial | trivial | harmful.

The distribution of abrasions incurred on the artificial turf alongside weekly rainfall values can be seen in Figure 6.4. The Pearson correlation coefficient for the relationship between weekly rainfall prior to the match and number of abrasion injuries was $r = -0.29$ (90% CI: -0.69 to 0.25, inference = 'unclear'). Two of the abrasion injuries recorded on artificial turf resulted in time loss, with severities of 6 and 13 days. The size and severity of abrasions incurred on the artificial surface are presented in Figure 6.5; the majority (69%) were second-degree abrasions, with 26%

first-degree and 5% third-degree (most severe). The mean area of recorded abrasions was 12.0 cm² (90% CI: 9.0 15.1). Abrasions were most commonly incurred on the knee (74%), followed by the lower leg (9%), elbow (7%) and forearm (4%). All abrasions were attributed a pain rating of between zero (no pain) and three (moderate pain) (Figure 6.6). Wingers, centres and flankers were the playing positions with the highest number of abrasion injuries (Figure 6.7).

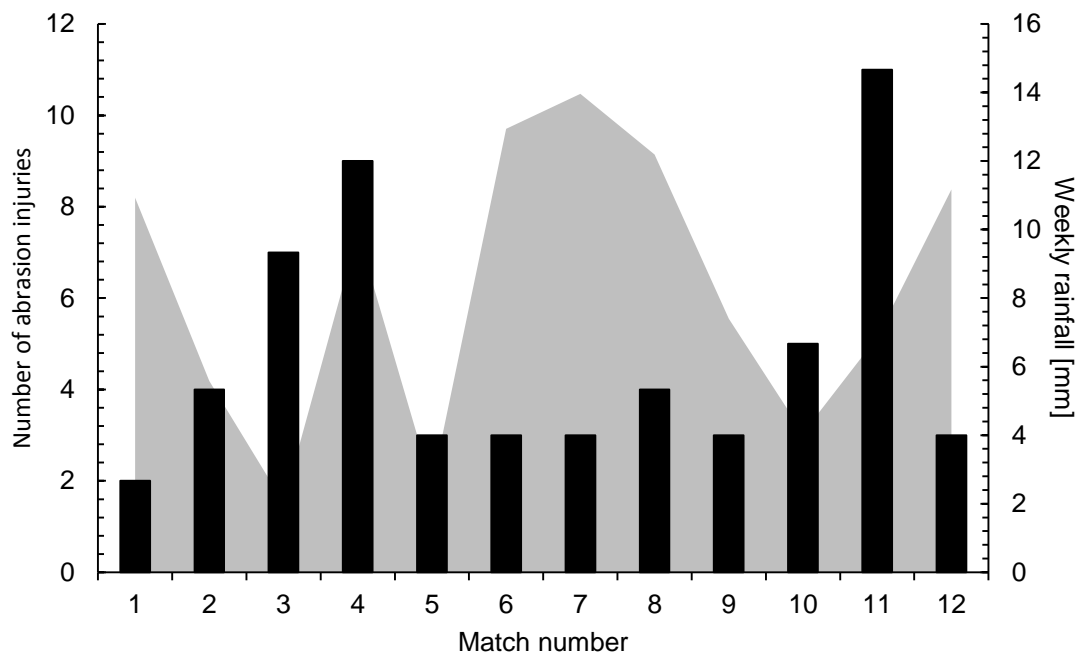


Figure 6.4 Number of abrasion injuries recorded for each match on artificial turf (black bars), alongside rainfall [mm] recorded during the week preceding the fixture (grey area).

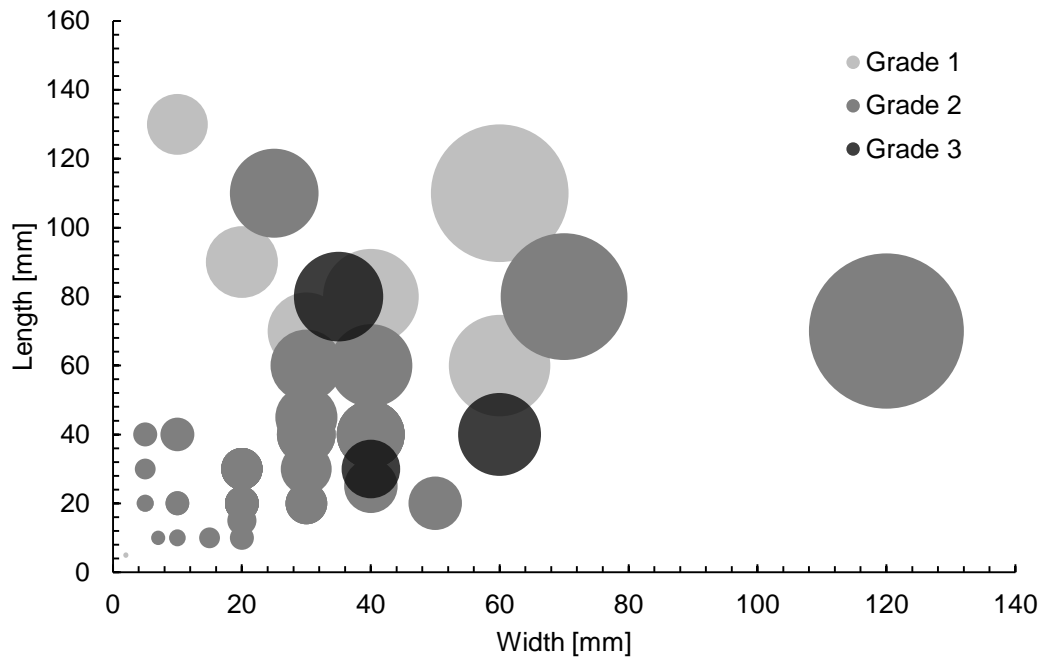


Figure 6.5 Bubble chart displaying the size and severity of abrasions incurred on the artificial surface.

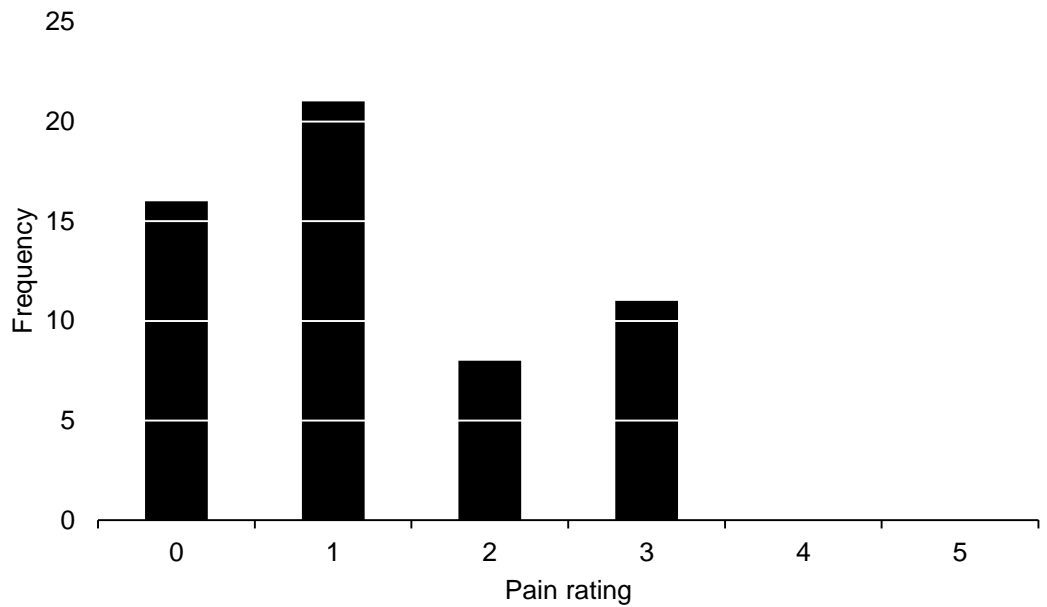


Figure 6.6 Distribution of pain ratings attributed to abrasions incurred on artificial turf immediately post-match [0=no pain, 1= minor pain, 3=moderate pain, 5= severe pain].

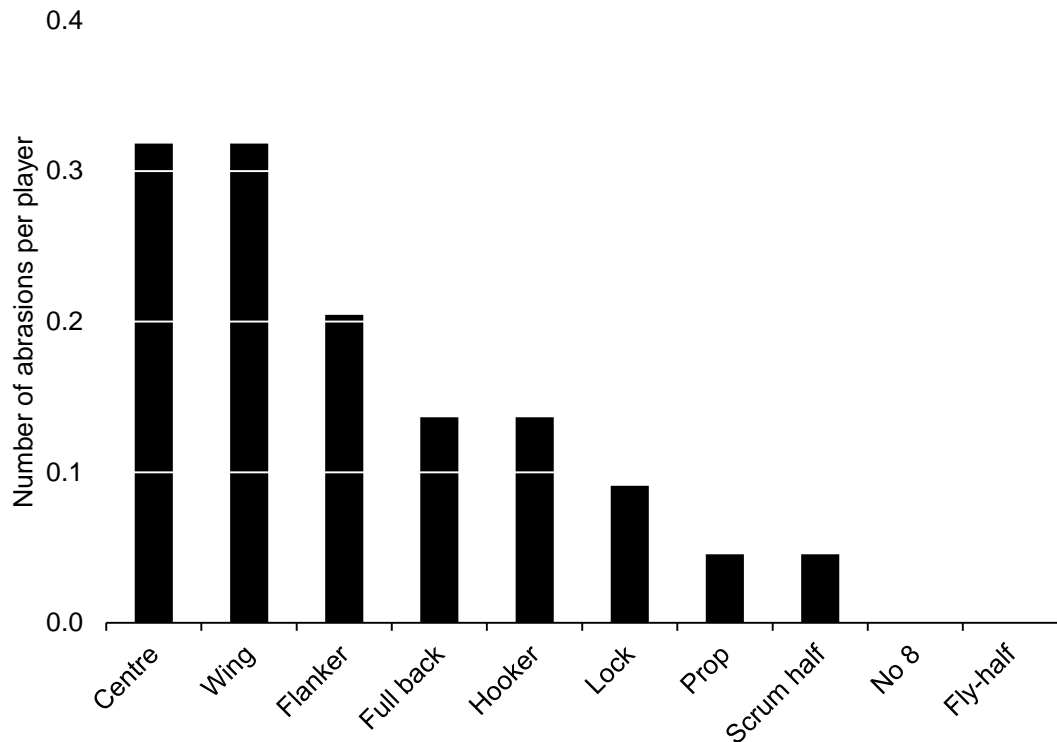


Figure 6.7 Distribution of abrasions across playing positions.

6.3.5 Muscle soreness

Reported muscle soreness from 95 players representing nine opposition teams were included in the analysis. This represents a response rate of ~70% of the total estimated population. Sufficient muscle soreness response data from the home team (who played regularly on the artificial playing surface) were not available to be included in the analysis. Perceived soreness peaked on day 1 post-match and then gradually decreased (Figure 6.8). Muscle soreness responses were consistently higher over the four days following a match on artificial turf in comparison with a match played on natural grass, although the magnitude of this effect was small, with effect sizes ranging from 0.26 (90% CI: 0.07-0.62) on day 1 to 0.40 (90% CI: 0.21-0.76) on day 4. The effect of the artificial surface on muscle soreness was statistically clear on each of the four days post-match.

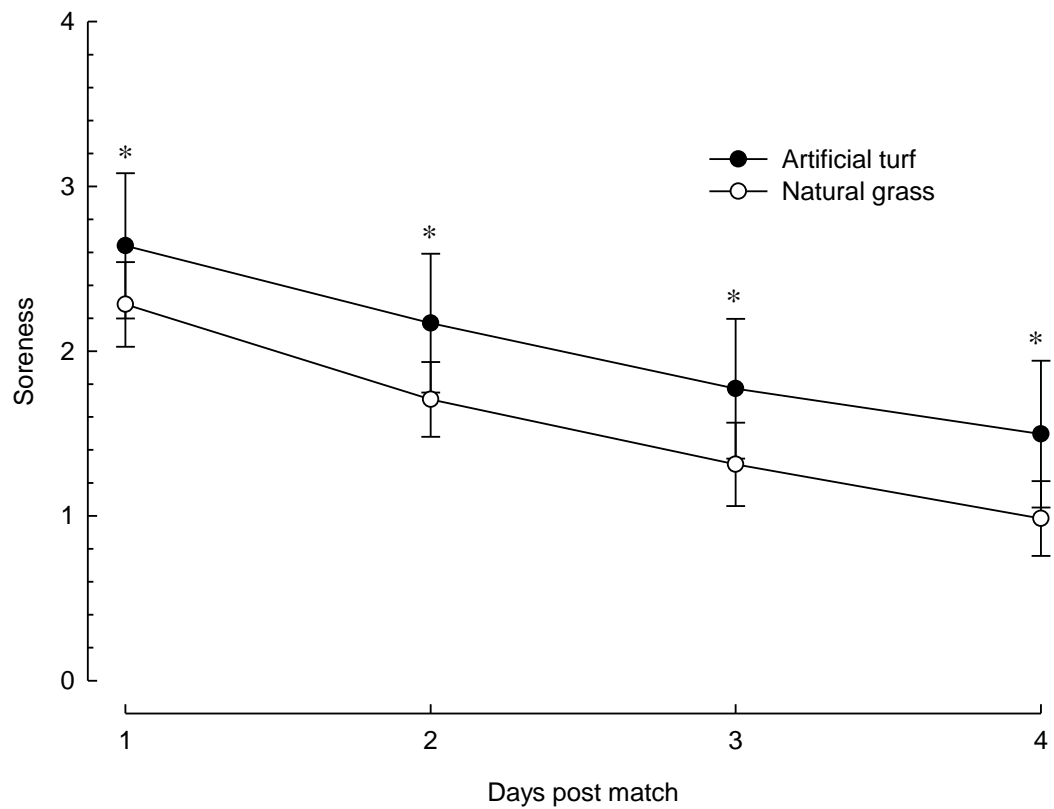


Figure 6.8 Reported general muscle soreness over the 4 days following a match on artificial turf (black circles) and natural grass (white circles). Values are means, bars are 90% CI. *, clear and substantial difference between surfaces.

6.4 Discussion

There were no clear differences in the incidence rate, severity or overall burden of time-loss injuries between the playing surfaces, based on thresholds set to detect moderate effects. Abrasions were substantially more common on the artificial turf, although the majority of these were minor and only two resulted in any reported time-loss from training or match play. Muscle soreness was consistently higher over the four days following a match on artificial turf in comparison with matches played on natural grass, although the magnitude of this effect was small.

Playing elite Rugby Union on an artificial surface does not appear to be associated with any substantial change in overall time-loss injury risk, which is similar to results reported for other team sports (Williams et al., 2011). However, several additional seasons of surveillance will be required before any smaller differences in overall injury risk (i.e., incidence rate ratio thresholds of 0.90 and 1.11) or variations in injury patterns may be detected. For instance, Fuller et al. (2010b) reported note-worthy differences in the incidence rate of anterior cruciate ligament injuries and ankle injuries when playing Rugby Union on an artificial surface compared to natural grass, although the differences were not statistically significant. Due to the relative scarcity of such injury events, considerable exposure time is required to detect any clear alterations in injury risk. Interestingly, the artificial surface in the present study was associated with a higher incidence rate of minor injuries (≤ 7 days) and a lower incidence rate of moderate injuries (8-21 days), resulting in a lower median injury severity. However, as the two injuries resulting in the greatest time-loss (183 and 134 days) were both incurred on the artificial turf, the mean severity of injuries and overall injury burden on the two surfaces was similar. A high incidence rate of scrum-related injuries was observed during the pilot study period, with an incidence rate of 36 per 1000 forward hours in comparison with a Premiership average of 10 per 1000 forward hours in 2011/12 (Taylor et al., 2014). However, no scrum injuries were recorded on the artificial turf during the 2013/14 season, resulting in an overall incidence rate of 12 per 1000 player hours (from the five scrum injuries reported across the whole study period). This change in injury pattern may be purely a result of natural sampling variation, but may also be indicative of a learning effect within forwards in relation to scrum technique on artificial turf, alongside dissemination of information regarding factors such as

optimal footwear choices for the surface. The nature and inciting event of injuries on artificial turf should be closely monitored in future seasons, in order to identify any potential differences in injury mechanisms between playing surfaces.

Abrasions were substantially more common on artificial turf in comparison with natural grass, with an average of 4.75 abrasions per match. More abrasions were recorded in fixtures where the previous week's rainfall had been low, although this relationship was not significant. Adding water to the surface may help to reduce skin abrasion effects, although whether this also modifies the risk of other forms of injury is currently unclear (van den Eijnde et al., 2014). Centres, wingers and flankers appear to be most at risk of abrasion injuries; the use of protective equipment (e.g. adhesive bandages, long-sleeve shirts) and skin lubricants may be of benefit in preventing abrasion injuries (van den Eijnde et al., 2014) and may be particularly useful for players in these positions. When all abrasions recorded during the pilot study are included, only two out of a total of 123 recorded abrasions resulted in any reported time-loss, demonstrating that acute skin injuries can be managed and treated effectively. Skin injuries are uncomfortable and unpleasant, and whilst they seldom lead to absence from training or match play, they require correct treatment to prevent complications. The risk of complications, in particular infections, appears to be low in professional players (who have frequent access to medical professionals) but abrasion treatment/management information (e.g. Basler et al., 2001) may be beneficial for youth and community level populations playing on artificial turf in order to avoid such issues. The current IRB recommendations for skin injuries state that players should be removed from the field of play until an appropriate dressing can be applied that prevents the leakage of body fluid and will help protect the lesion from becoming infected (International Rugby Board, 2010). The guidelines also state that careful attention should be paid to the wound after play in order to avoid skin infections, but do not provide specific details regarding abrasion treatment/management.

Muscle soreness responses were consistently higher on the four days following a match on artificial turf in comparison with a match played on natural grass, although the magnitude of this effect was small. This finding is in agreement with results reported for professional soccer players (Poulos et al., 2014). Several studies have

been conducted that suggest the mechanical properties of a playing surface (e.g. its stiffness and traction) influence the kinematics and kinetics of running, with associated changes in metabolic and physiological responses (Hardin et al., 2004; Kerdok et al., 2002). The playing surface may also change the nature of the game itself (e.g. running speeds, ball-in-play time and concomitant fatigue levels), as has been reported in other sports (Norton et al., 2001; Gains et al., 2010; Di Michele et al., 2009; Andersson et al., 2008).

Perceptions of muscle soreness have been shown to correlate with biochemical markers of muscle damage following exercise (Clarkson and Tremblay, 1988). However, self-reported muscle soreness measures could be subject to misinterpretation of the questions being asked, as well as participant expectancy effects (McGrath et al., 2014). Additionally, the home team won eleven of the twelve matches on the artificial surface; losing has been shown to produce strong unpleasant emotional changes in rugby players (Wilson and Kerr, 1999), and so this may also have contributed towards the higher muscle soreness reported by the away team following matches played on the artificial turf compared with natural grass. What's more, losing teams are typically involved in more tackle situations (van Rooyen et al., 2014), which have in turn been correlated with objective measures of muscle soreness in elite Rugby Union players (Cunniffe et al., 2010), and so these differences in match activities may also have contributed to the observed results. Given that the visiting teams' players rarely play competitive matches on an artificial surface, it may be that the unfamiliar characteristics of the playing surface resulted in the small elevation in muscle soreness on the days following the match, which may subsequently diminish with future exposure (within several months) to the same surface due to the repeated bout effect (McHugh et al., 1999). Unfortunately, sufficient muscle soreness response data from the home team (who played regularly on the artificial playing surface) were not available to provide clear evidence of this effect. Knowledge of how players respond to and recover from matches is important for team-sport coaches when considering the subsequent week's training and match demands (Montgomery and Hopkins, 2012). Over the four days following a match on artificial turf, coaches of teams that do not play matches regularly on such surfaces can expect players' muscle soreness to be slightly higher in comparison with matches played on natural grass. These data may be useful for coaches when

planning training and recovery protocols following fixtures played on an artificial surface.

A limitation of the current study is that an inter-cohort comparison between teams playing on artificial turf at their home facility versus teams playing on natural grass at their home facility was not possible, due to the fact that only one Premiership team had an artificial surface installed during the study period. In a study involving professional football teams (n=32), no substantial differences were found in acute injury rates between playing surfaces at the individual player level, but it was revealed that teams who played on artificial turf at their home facility had higher rates of overuse and acute training injuries compared with teams that played their home matches on natural grass (Kristenson et al., 2013). As the number of professional Rugby Union teams using artificial surfaces at their home facility increases (the number of teams with an artificial turf pitch installed has already increased to three since the beginning of the current study period), such analyses will be possible and will allow for a more complete understanding of how artificial playing surfaces influence injury risk in this population. An additional potential limitation of the current study is that some teams may have elected to rest certain players for their match on the artificial surface (e.g. joint or tendon compromised players) due to concerns regarding their injury risk, and so the absence of these players may have biased the results in favour of the artificial turf.

6.4.1 Conclusion

The present study was the first to investigate the influence that an artificial playing surface has upon time-loss and abrasion injury risk, and perceptions of muscle soreness in elite Rugby Union players. There were no clear differences in the incidence rate, severity or overall burden of time-loss injuries between the playing surfaces. However, due to the size of the sample population, further surveillance is required before inferences regarding specific injury diagnoses, for example ACL injury risk, and smaller differences in overall injury risk between the playing surfaces can be made. Abrasions were substantially more common on the artificial turf, although the majority of these were minor and only two resulted in any reported time-loss from training or match play, therefore the abrasions incurred on artificial turf can generally be appropriately managed to reduce impact. Muscle soreness for

unaccustomed players was consistently higher over the four days following a match on artificial turf in comparison with matches played on natural grass, although the magnitude of this effect was small. These results provide evidence to support the current and future use of artificial playing surfaces in elite Rugby Union, so long as continued surveillance is undertaken to allow analyses of specific injury diagnoses and smaller overall differences in injury risk to be carried out. Moreover, the long term risks associated with playing Rugby Union on artificial turf warrant investigation.

CHAPTER SEVEN

Previous Injury and Match Load as Risk Factors for Injury in Elite Rugby Union Players: Application of a Frailty Model for Recurrent Events

7.1 Introduction

The identification of risk factors for injury, especially modifiable ones, is a key component in the development of effective injury prevention strategies (van Mechelen et al., 1992). While numerous studies have documented the incidence rate and nature of injuries in elite Rugby Union (for review, see Chapter 3), few have gone on to identify specific risk factors using appropriate statistical methods that account for the dynamic, recursive nature of injuries (Meeuwisse et al., 2007). Previous injury and match loads have been identified as potential risk factors for injury in other sporting populations, but no studies investigating these variables in elite Rugby Union populations have been undertaken to date.

Previous injury is often proposed as a risk factor for subsequent injury (de Visser et al., 2012; Hägglund et al., 2006; Hamilton et al., 2011a; Swenson et al., 2009). It is postulated that following an injury, alterations to a player's intrinsic risk factors may occur (e.g. altered movement patterns, loss of balance, or other psychological/functional impairments), which may modify the player's future predisposition to injury (Fyfe et al., 2013; Meeuwisse et al., 2007). However, this is yet to be examined appropriately within elite Rugby Union populations. Being injured at the beginning of the season was identified as a significant risk factor for both the incidence of injury and time lost due to injury during the season in community level Rugby Union players, but previous injury did not elevate injury risk when players entered the current season injury free (Quarrie, 2001). Similarly, Chalmers et al. (2012) found no evidence of an association between a history of injury in the past 12 months and risk of in-season injury amongst a similar cohort of community level Rugby Union players. However, such results cannot be generalised to an elite Rugby Union population. Moreover, the use of self-reported medical history data in these studies means that recall bias may have occurred. Bias is also introduced in studies of this nature because individual predispositions toward injury are not accounted for. Indeed, Hamilton et al. (2011b) used conditional analyses (i.e.

time to first, second and third injuries among individuals with three or more injuries) within a matched population of circus artists and reported that previous injury was not associated with an increased risk of subsequent injury for a given individual. Instead, previous injury was simply a marker for other traits (e.g. poor technique) that caused an individual to have a greater injury risk. What is more, the influence of an athletes' previous injury *load* on current injury risk, which accounts for the number, severity and recency of previous injuries, remains to be examined in any athletic population. Such a measure may account for the dynamic, recursive nature of injury risk in a more complete manner (Meeuwisse et al., 2007).

There appears to be a growing concern over the demands being placed on professional Rugby Union players with regards to the number of matches they are expected to play (James, 2014b; James, 2014a). There is qualitative and anecdotal evidence to suggest that a high match load over the course of a Rugby Union season, perhaps combined with limited recovery in the off-season, increases the risk of player 'burnout' and may augment injury risk in the following season (Cresswell and Eklund, 2006). However, no quantitative data exist to support these findings concerning the delayed impact of match loads on injury risk. Meanwhile, several studies have reported an association between fixture congestion and injury risk in elite football players (Dellal et al., 2013; Dupont et al., 2010; Bengtsson et al., 2013). Additionally, changes in match load (calculated by multiplying the match intensity by the time each player participated in the match) were positively correlated with changes in the incidence rate of match injuries in semi-professional rugby league players (Gabbett, 2004). Together, these findings suggest that a higher number of matches played in the period leading up to a given match may increase injury risk, but this is yet to be investigated in Rugby Union. To date, the temporal effect of match load on injury risk in elite Rugby Union players remains to be elucidated.

Repeated injury events within an individual elite Rugby Union player are common (Chapter 5; Figure 5.3), and are likely to be related via a risk factor or injury mechanism to which the individual is exposed (Cook, 2010). Although sport injury data often contain repeated events within individuals, few published studies have considered the correlation amongst such events (Mahmood et al., 2014). Clustering can also occur at a group level, such as within a team due to a particular coaching

philosophy for example, and so the Poisson assumption of independence between events is not correct within such recurrent injury data (Hayen, 2006). Appropriate statistical techniques must therefore be used in order to account for the additional variance that these repeated injury events have upon confidence intervals (Glynn and Buring, 1996): failure to do so may result in artificially narrow confidence intervals and thus erroneous inferences regarding the data (Cook, 2010). For instance, the Cox Proportional Hazards model (Cox PH) is a class of survival model that only considers time to the first injury, and so provides a poor fit for recurrent sport injury data (Ullah et al., 2012). The frailty model accounts for the clustering present in event time data, and has been identified as the most appropriate statistical model for recurrent sport injury data of this nature (Ullah et al., 2012).

In light of the extant literature presented above, it appears that the effects of previous injury and match loads on injury risk are yet to be examined appropriately within elite Rugby Union populations. As such, this study sought to investigate the role that previous injury load, match load in preceding season, and match load in 30 days prior to injury have upon injury risk in elite professional Rugby Union players, through the application of a frailty model for recurrent events.

7.2 Methods

7.2.1 Study design and setting

A seven-season prospective cohort design (as per Chapter 4) was used to record all match and training injuries associated with professional Rugby Union players at 15 English Premiership teams, according to agreed protocols as part of the Professional Rugby Injury Surveillance Project (PRISP). Injury and exposure data were returned to a study investigator at the academic host institution of the PRISP (2006-2011, Nottingham University; 2011-2013, University of Bath). Data collected from the twelve league teams in each of the seasons between 2006/07 and 2012/13 were collated as part of this Ph.D. This injury database was upheld by the academic host institution of the PRISP.

7.2.2 Participants

All consenting players that were members of the first team squad were eligible for inclusion. Data pertaining to a total of 1253 professional Rugby Union players was included in the analysis. The study was approved by the research ethics committee of the academic host institution where the PRISP was based for each season, and written informed consent was obtained from each participant. All data were anonymised.

7.2.3 Variables

The definitions and procedures used in this study were consistent with the international consensus statement for epidemiological studies in Rugby Union (Fuller et al., 2007c). The primary (time-loss) injury definition used in this study was:

‘Any physical complaint sustained by a player during a first-team match that prevented the player from taking a full part in all training activities typically planned for that day, and/or match play for more than 24 hours from midnight at the end of the day the injury was sustained’.

All injuries were recorded by medical personnel at each team using a modified Orchard Sports Injury Classification System (OSICS) (Orchard, 1995) and standard injury report form. Individual match and group training exposure data was reported weekly by each team. Training was defined as:

‘Any team-based or individual physical activities performed under the guidance of the team’s coaching or fitness staff, which are aimed at maintaining or improving players’ rugby skills or physical condition.’

It was assumed that individuals were involved in training sessions unless they were currently injured. The number of equivalent matches played was calculated by dividing a player’s total match exposure (in minutes) over the given period by 80.

Three potential risk factors for injury were assessed: a player’s previous injury load (injury load); the number of equivalent matches played in the preceding season (previous season match load), and the number of equivalent matches played in the previous 30 days (month match load). A player’s injury load was the product of their ‘smoothed injury severity’ and the number of injuries they had previously incurred; the ‘smoothed injury severity’ parameter used a weighted average of a player’s previous injury severities based on the number of days between the current injury episode and each previous occurrence, using an inverse natural log scale [Eq. 7.1]:

$$\text{Weighted Average Severity} = \frac{\sum_{i=1}^n 1/\ln(t_i) \times s_i}{n} \quad \text{Eq. 7.1}$$

Where t_i was the time in days between the present injury and the i^{th} previous injury event, s_i was the severity of the i^{th} previous injury and n was the number of previous injury events incurred by the given player. That is, the severity of more recent injury events had a greater weighting in the calculated average than the severity of older injury occurrences. The injury load variable was then log-transformed to obtain an approximately normal distribution. All of a player’s recorded injuries were included in the injury load calculation. Additionally, a ‘number of previous injuries’ variable was assessed as a risk factor for injury; this variable was a more simplistic measure of a player’s previous injury history, in order to evaluate the efficacy of the ‘injury load’ variable.

7.2.4 Statistical methods

Survival models were applied to the injury data set to calculate the adjusted hazard ratios (HR) of injury incidence with 90% CI for each of the assessed risk factors. The HRs were adjusted by controlling for players’ age and grouped playing position (forward or back). Models were fitted using the *Coxme* package (Therneau, 2012)

with R (version 3.0.3, R Foundation for Statistical Computing, Vienna, Austria). Three forms of survival model were applied: a Cox PH model (i.e. a survival model without random effects; Cox, 1972); a shared frailty model that used a single random effect to describe within-player grouping in the data; and a nested frailty model, which used two random effects to describe hierarchical grouping in the data (i.e. within-team and within-player correlations). To allow the computation of the nested frailty model, each player was assigned the team for which they incurred the highest number of injuries. Time in calendar days was used as the exposure measure, to ensure that players were not at risk during recovery periods (Wassell et al., 1999), and to allow for event dependence (Box-Steffensmeier and De Boef, 2006). As some players appeared in multiple seasons, each season was handled as an independent observation period in the frailty model. Non-informative censoring was used, with all surviving (non-injured) players contributing censored survival times at the end of each season.

The log likelihood (LL), Akaike information criterion (AIC) and Bayesian information criterion (BIC) were used to assess and compare the goodness of fit of each of the survival models (Cameron and Trivedi, 2013; Dayton, 2003), with lower values indicating a better fit to the observed data (Burnham and Anderson, 2004). The *anova.coxme* function was used to compare the change in LL for each survival model, with significance accepted at an α level of $P \leq 0.05$. A difference in AIC and BIC values of >2 was accepted as evidence of substantial differences (Hardin et al., 2007). Model accuracy was also evaluated using a likelihood-ratio based pseudo-R-squared value, which was extracted using the *MuMIn* package in R version 3.0.3 (R Foundation for Statistical Computing, Vienna, Austria). The same model evaluation measures were used to compare model performance when the ‘number of previous injuries’ variable was included in the best-fitting survival model (alongside the previous season match load, month match load, age and grouped playing position variables), in comparison with the calculated ‘injury load’ variable. Modified Wald tests were used to determine whether the variance parameter from the frailty models was significantly different from zero (Molenberghs and Verbeke, 2007). The critical value for a normal one-sided test was 1.64. Results pertaining to the effect of the three risk factors on injury risk are only presented for the best-fitting survival model.

The effect of each risk factor on overall injury risk was estimated by multiplying the coefficients, obtained from the best-fitting survival model, by a load equal to 2 between-subject standard deviations; this value represents the difference in injury risk for those with typically high versus typically low values of the risk factor (Hopkins et al., 2009a). Further examination of whether responses were non-linear were also undertaken, as recommended by Gabbett et al. (2012a). If assessment of a quadratic trend for a given risk factor yielded additional meaningful information, the continuous variable was subsequently parsed into quintiles (with the lowest range being the reference group) to observe the pattern of injury risk across the full range of values of the risk factor.

Both training and match injuries were included in the initial analyses. Subset analyses of specific injury types (severe, acute, gradual onset, contact, non-contact, recurrent, match and training) were also undertaken, to determine their relationship with the three risk factors. For these, each risk factor was dichotomised according to whether a given value was above or below the median value, to aid computation and reduce the likelihood of having too many cells with small counts in the model. Severe injuries were classified as those resulting in greater than 28 days of time-loss. Recurrent injuries were defined as injuries to the same site and of the same type as a previous injury. The onset of the injury (acute/gradual) was classified by medical personnel at the time of recording the injury. The nature of the injury (contact/non-contact) was determined from the injury incident. For the injury load variable, all of a player's recorded injuries were included in the calculation. For the survival models and injury incidence rate values (Figure 7.2), only injuries that occurred in matches for which exposure was recorded (i.e., first-team competitive matches) were included in the analyses.

Magnitude-based inferences were used to provide an interpretation of the real-world relevance of the outcome, based directly on uncertainty in the true value of the effect statistic in relation to a smallest worthwhile effect (Batterham and Hopkins, 2006). The smallest worthwhile increase in risk (i.e. harmful effect) for time-loss injuries was a hazard ratio of 1.11, and the smallest worthwhile decrease in risk (i.e. beneficial effect) was 0.90 (Hopkins, 2010). An effect was deemed unclear if its confidence interval overlapped the thresholds for substantiveness by >5%; that is, if

the effect could be substantial in both a positive and negative sense. Otherwise the effect was clear and deemed to have the magnitude of the largest observed likelihood value. This was qualified with a probabilistic term using the following scale : <0.5%, most unlikely; 0.5-5%, very unlikely; 5-25%, unlikely; 25-75%, possible; 75-95%, likely; 95-99.5%, very likely; >99.5%, most likely (Hopkins, 2007). The same approach was used to determine whether each of the subset analyses differed substantially from the ‘all injuries’ estimate.

The required sample size was estimated using the *powerSurvEpi* library in R version 2.15.1 (Latouche et al., 2004). For 80% power and an alpha value of 0.05 to detect a hazard ratio of 1.11, the minimum required number of injuries to be modeled was 2295. A variance inflation factor (VIF) analysis was used to assess for multicollinearity between predictor variables, with a value ≥ 5 considered as evidence of multicollinearity (Quinn and Keough, 2002). No evidence of multicollinearity was found (VIF = 1.02-1.16).

7.3 Results

7.3.1 Participant characteristics

The physical characteristics of participants across the included seasons are displayed in Figure 7.1. It was important to confirm that the population's physical characteristics remained stable throughout the study period; no substantial differences between seasons were evident.

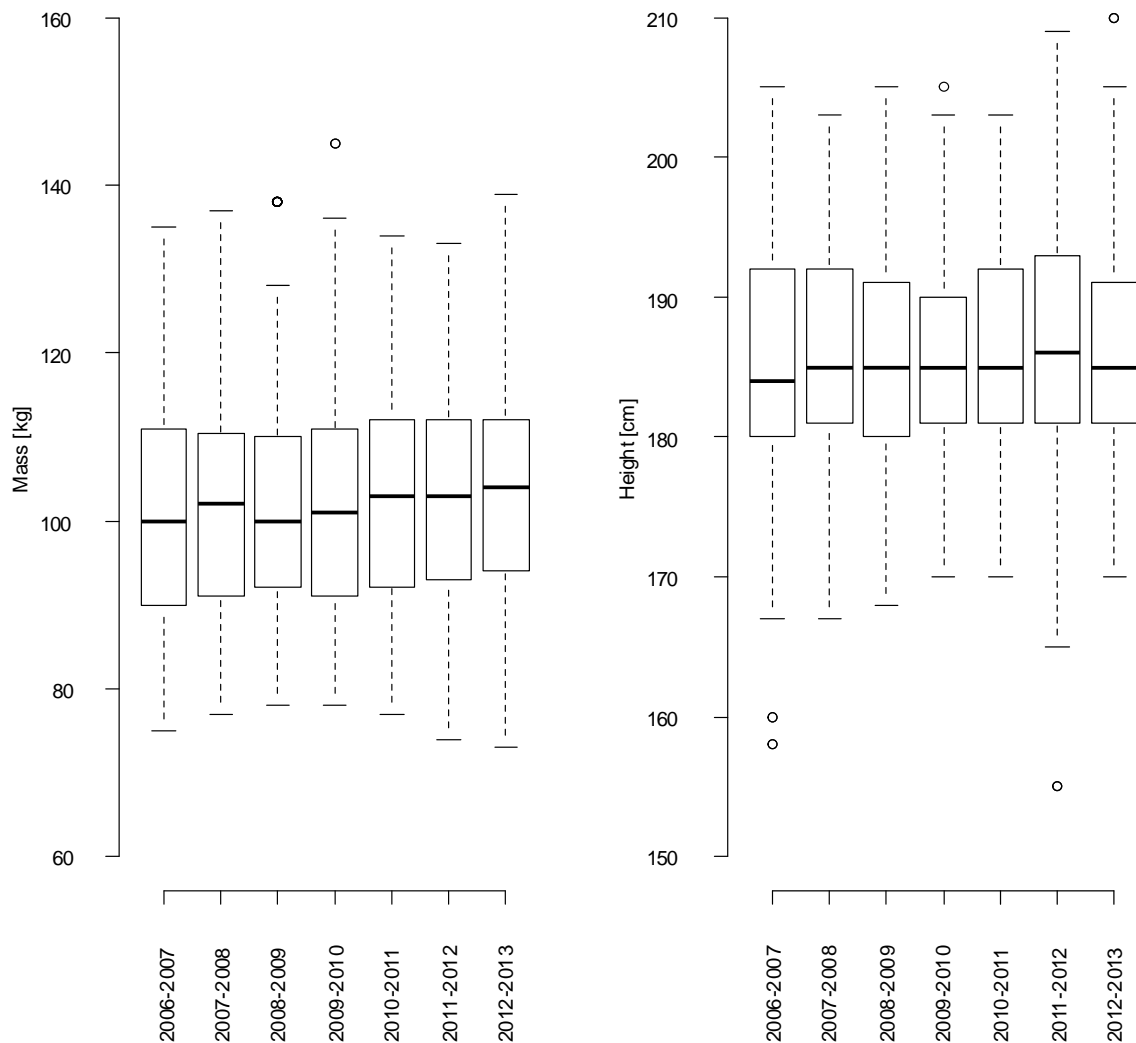


Figure 7.1 Boxplot summaries of players' mass and height across the included seasons. Outliers were defined as being more than 1.5 times the interquartile range above/below the upper and lower quartiles, respectively.

7.3.2 Injury incidence rates

A total of 6890 time-loss injuries were recorded over the study period. Figure 7.2 shows the match and training injury incidence over the seven seasons. The average match injury incidence rate over the study period was 85.9 ± 9.0 per 1000 player h,

and 2.8 ± 0.4 per 1000 h for training injuries. Of the included players, 78% incurred two or more time-loss injuries.

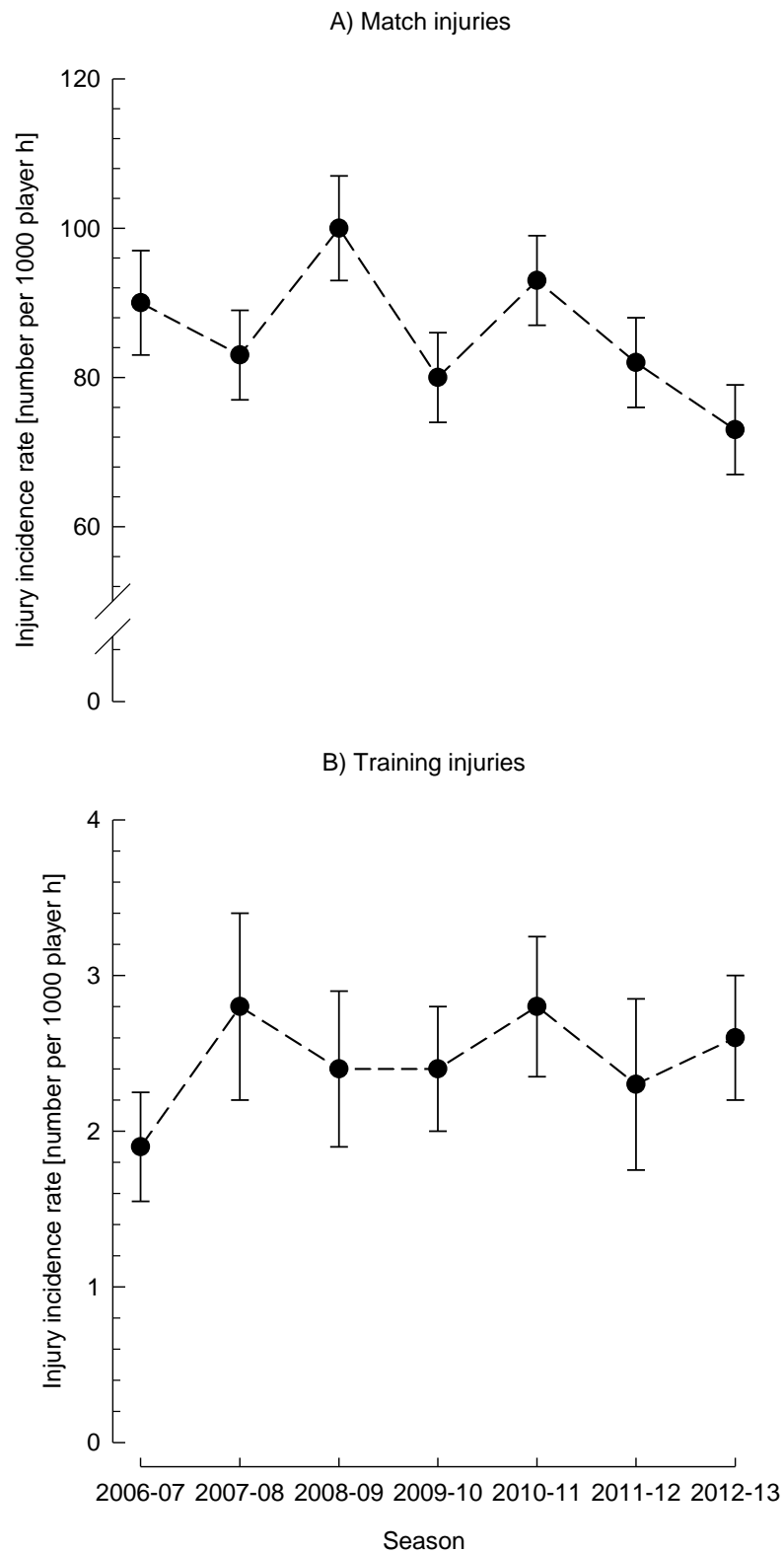


Figure 7.2 Injury incidence rate of A) match and B) training injuries across the included study seasons, with 95% CI.

7.3.3 Model selection

After exclusion of players with zero match exposure in the preceding season, a total of 4725 injury events were included in the analyses. Table 7.1 displays the LL, AIC, BIC and R-squared value for the fitted survival models. The nested frailty model performed substantially better than the Cox PH and shared frailty model. Figure 7.3 shows an example of the injury timelines of three players, and demonstrates the complex nature of recurrent sport injury data.

Table 7.1 Model selection criteria (log likelihood [LL], Akaike information criterion [AIC], Bayesian information criterion [BIC] and R^2) for the three fitted survival models. ^a denotes substantial improvement compared with Cox PH model fit and ^b denotes substantial improvement compared with shared frailty model fit

Model	Model selection criteria			
	LL	AIC	BIC	R^2
Cox PH	-36931	73871	73904	.036
Shared frailty	-36864 ^a	73741 ^a	73779 ^a	.132
Nested frailty	-36852 ^{a,b}	73719 ^{a,b}	73763 ^{a,b}	.133

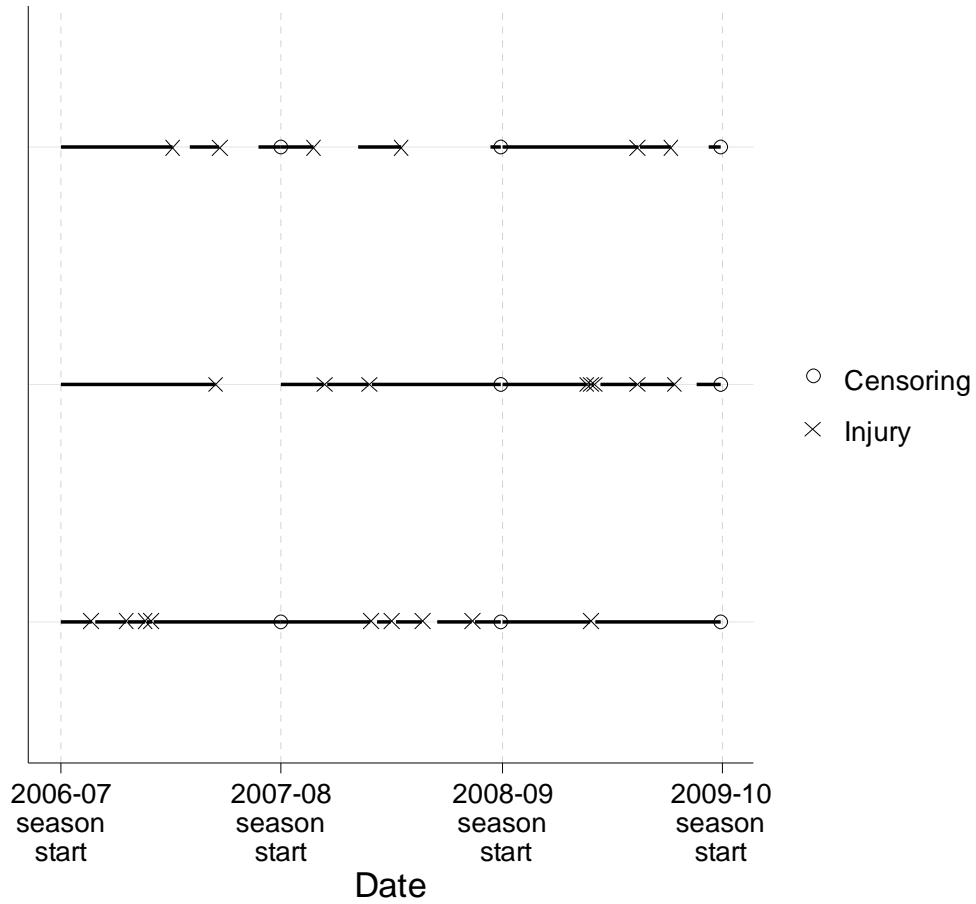


Figure 7.3 Example of recurrent injury history of three players. Time-loss injury events are denoted by a cross (x). Censored data is denoted by a circle (o). Note, gaps in the timeline represent periods when the player was absent due to injury.

7.3.4 Heterogeneity between teams and players

The variance parameter from the shared frailty model was 0.120 (standard error [SE] = 0.016). As $\frac{0.120}{0.016} = 7.50$, this value was greater than the critical value of 1.64 and therefore provides evidence of heterogeneity in injury risk between individual players. From the nested frailty model, both the group $\left(\frac{\alpha}{SE(\alpha)} = \frac{0.007}{0.002} 3.5 > 1.64\right)$ and subgroup $\left(\frac{\pi}{SE(\pi)} = \frac{0.206}{0.034} = 6.059 > 1.64\right)$ random effects were significant; this provides evidence of clustered survival times within both teams and individual players.

7.3.5 Injury risk factors

The nested frailty model provided the best fit of the observed data, and so all presented results relating to the effect of the studied risk factors were obtained from the nested frailty model. After appropriate adjustment for players' age and grouped playing position, injury load and previous season match load were significant predictors of overall injury risk. Players with a high previous injury load and high previous season match load had a substantially higher risk of injury. Inferences relating to the month match load variable were unclear (Figure 7.4).

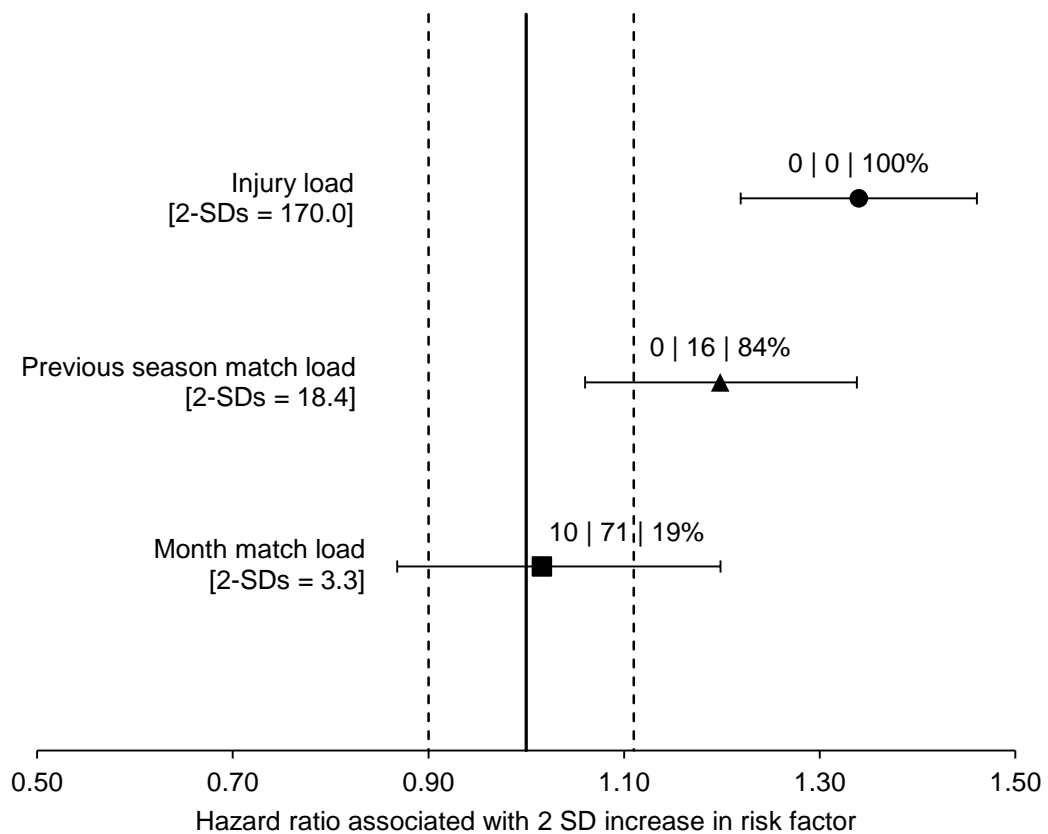


Figure 7.4 Hazard ratio (from nested frailty model) associated with a 2 SD increase in each risk factor (injury load, previous season match load and month match load). All HR's were adjusted for player age and grouped playing position. Dotted lines represent thresholds for smallest worthwhile difference (0.90 and 1.11). Data labels display the % likelihood that the effect is beneficial | trivial | harmful.

7.3.6 Non-linear relationships

Evidence of a non-linear relationship was found for the injury load variable only. There was a substantial increase in injury risk for all injury load ranges above the baseline group (i.e., >139 AU), with no clear differences between other range groups (Figure 7.5).

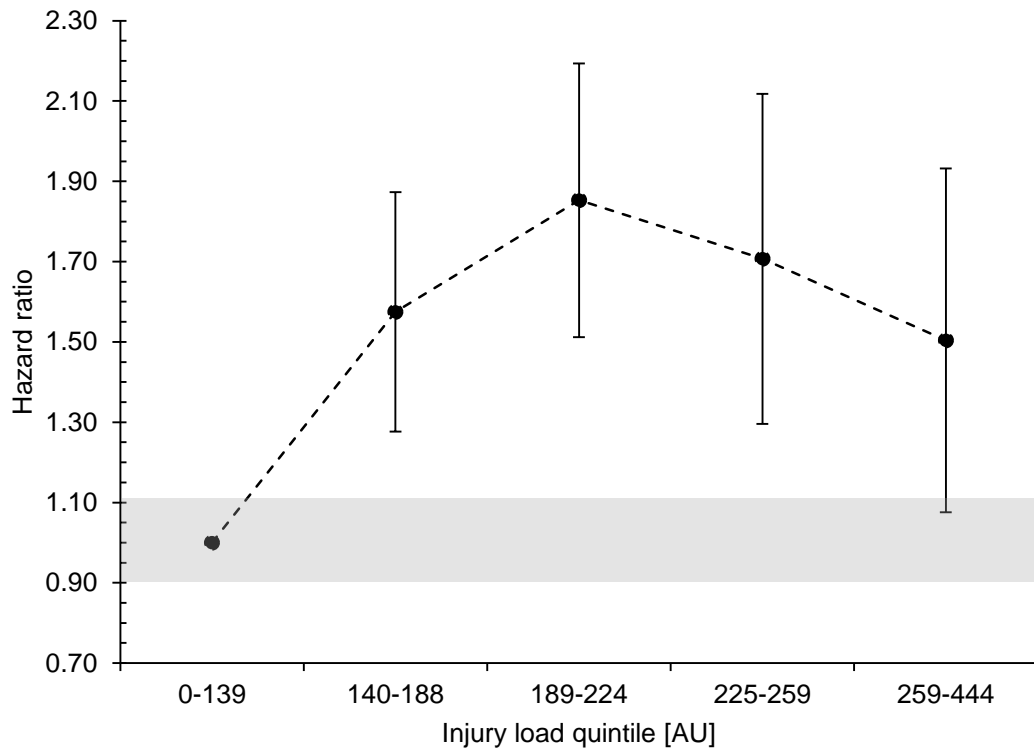


Figure 7.5 Non-linear relationship between injury risk (hazard ratio) and injury load quintiles. Shaded area represents a trivial change in injury risk (HR: 0.90-1.11).

7.3.7 Injury load variable

The ‘injury load’ variable provided a substantially better fit of the observed data when compared with ‘number of previous injuries’ variable (Table 7.2). An example of one player’s injury load across the study period is displayed in Figure 7.6. The player’s injury load fluctuates across the study period, depending on the number, severity and recency of previous events (as described by Eq. 7.1).

Table 7.2 Model selection criteria (log likelihood [LL], Akaike information criterion [AIC], Bayesian information criterion [BIC] and R^2) for the ‘number of previous injuries’ and ‘injury load’ variables within the nested frailty model. ^adenotes substantial improvement compared with the ‘number of previous injuries’ variable

Variable	Model selection criteria			
	LL	AIC	BIC	R^2
Number of previous injuries	-36905	73802	73869	.106
Injury load	-36852 ^a	73719 ^a	73763 ^a	.133

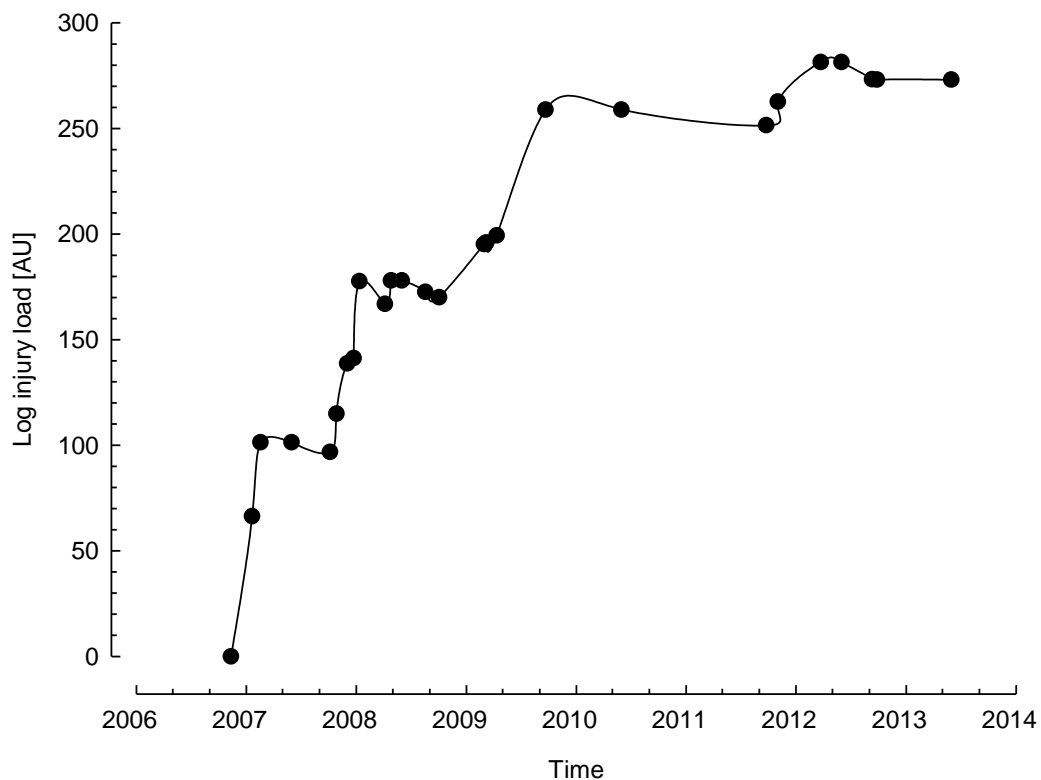


Figure 7.6 An example of one player’s injury load values across the study period. Closed circles represent injury events.

7.3.8 *Subset analyses*

Results of the subset analyses of specific injury types are presented in Figure 7.7. Injury load was a substantially stronger predictor of severe injuries than all injuries. The magnitude of the injury load variable as a predictor was reduced for recurrent injuries, but remained clearly harmful. Previous season match load was a substantially stronger predictor of training injuries than all injuries. The estimate of the month match load variable as a risk factor was reduced for non-contact and training injuries, with the inference changing from ‘trivial’ to ‘possibly beneficial’ for non-contact injuries, but remained as ‘trivial’ for training injuries. All other findings were trivial or unclear.

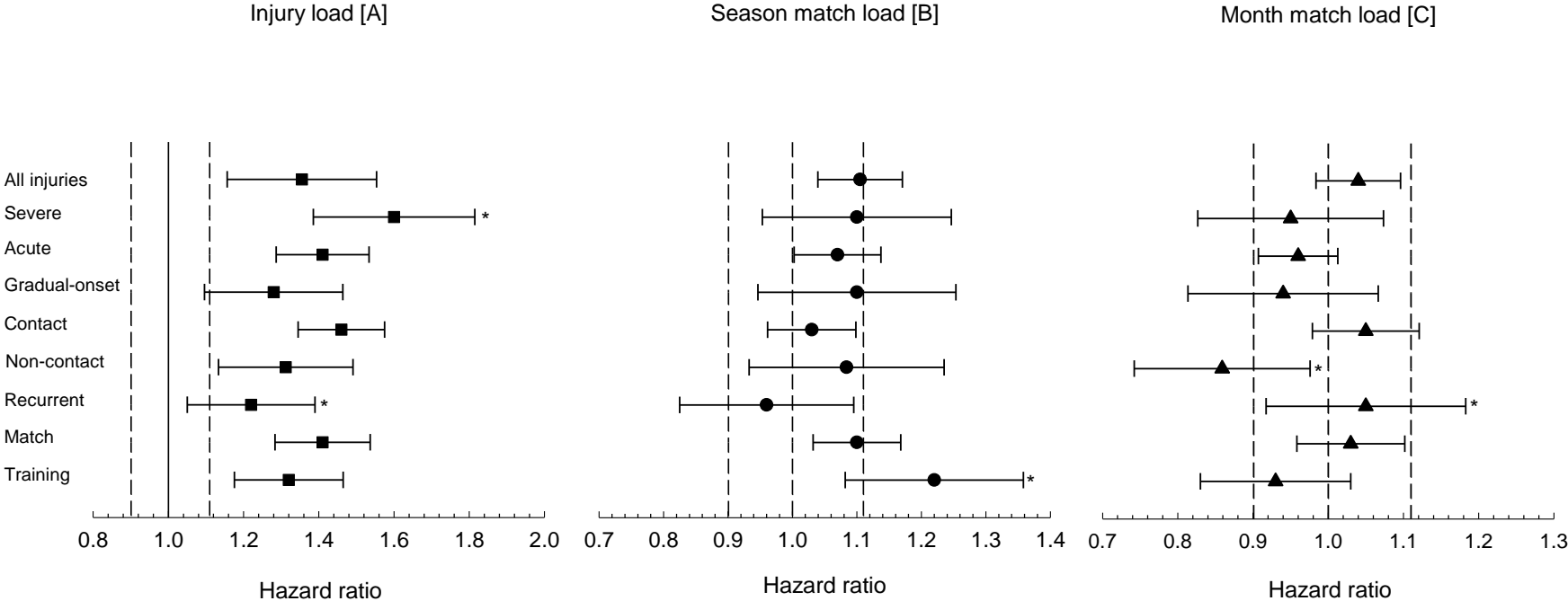


Figure 7.7 Subset analyses of specific injury types using the nested frailty model for each of the predictor variables: [A] injury load, [B] previous season match load and [C] month match load. All HR's were adjusted for player age and grouped playing position. Dotted lines represent thresholds for smallest worthwhile difference (0.90 and 1.11). *, substantial difference from 'all injuries' result. For these analyses, each risk factor was dichotomised according to whether a given value was above or below the median value.

7.4 Discussion

This is the first study to investigate previous injury loads, previous season match loads (match load in preceding season) and month match loads (match load in 30 days prior to injury) as risk factors for injury in professional Rugby Union players. The results demonstrate that players with high previous injury loads, and those who have played a high number of matches in the preceding season, have an increased overall injury risk in the current season. A player's match load in the preceding 30 days is not clearly associated with risk of injury. In comparison with their association to overall injury risk, previous injury loads have a greater association with the risk of incurring severe injuries, previous season match loads display a greater association with training injury risk, and high month match loads are associated with a reduced risk of non-contact injuries.

Playing a high number of matches in the preceding season was shown to be associated with an increased risk of injury in the current season. Injury risk increased linearly with previous season match load, with no evidence of a non-linear relationship. In qualitative investigations, professional Rugby Union players have attributed factors such as heavy playing loads, limited recovery time in the off-season, and an 'anti-rest culture' as causes for burnout syndrome and increased injury incidence (Cresswell and Eklund, 2006). The results of the current study concur with these findings, and provide the first quantitative evidence of an increased injury risk when a high number of matches are played in the preceding season. England's elite playing squad are currently restricted to playing a maximum of 32 matches per season, but this remains higher than the 25 matches that elite Southern Hemisphere players typically play per season (unpublished observations). The seven match difference between these settings is associated with a ~10% increase in injury risk in the subsequent season. A small reduction in the current match load limit should therefore be considered. Subset analyses revealed a stronger relationship between previous season match load and risk of training injuries risk (compared with all injuries), suggesting that players with high previous season match load values are less able to cope with the demands of training during the following season. As such, players with high previous season match loads may benefit from modified recovery and training load strategies, in order to help them cope with the demands of training in the subsequent season.

High previous injury loads were associated with a substantially increased risk of injury. In addition, the relationship between injury load and current injury risk followed an ‘inverted-U’ shaped curve, with an apparent peak in injury risk in the range of 189-224 AU. The small reduction in risk associated with injury load values in the top two quintiles (>224 AU), compared with the third quintile (189-224 AU), may be indicative of the fact that such individuals have experienced severe injuries, and/or a high number of previous injury events, and so it is possible that these players are managed in a way that reduces their subsequent injury risk compared with players with a moderate injury load. However, it should be noted that the small decrease in injury risk for those in the top two quintiles of injury load (compared with the third quintile) was not *clearly* beneficial. In agreement with the majority of current research (de Visser et al., 2012; Hägglund et al., 2006; Hamilton et al., 2011a; Swenson et al., 2009), past injuries were shown to influence a player’s subsequent injury risk, although this is the first study to investigate this relationship amongst elite Rugby Union players. Following an injury, alterations to a player’s intrinsic risk factors may occur (e.g. altered movement patterns, loss of balance, or other psychological/functional impairments), which may modify the player’s future predisposition to injury (Fyfe et al., 2013; Meeuwisse et al., 2007). The subset analyses revealed a stronger association between the injury load variable and risk of incurring severe (>28 days) injuries, in comparison with its association to overall injury risk. This finding implies that the cumulative damage associated with past injuries, and the likely effect such damage has upon a player’s intrinsic risk factors, increases the risk of incurring injuries that result in substantial time-loss. It may be that modified recovery and rehabilitation strategies are required for players with high previous injury loads, in order to help reduce the injury burden associated with this risk factor.

By monitoring each player’s injury load across a season, teams can identify when players go beyond the threshold value of 139 AU, and put in place measures (e.g. reduced training/match loads or bespoke rehabilitation measures) in order to alleviate the injury risk. As an illustrative example, the injury load variable for the player demonstrated in Figure 7.3 went beyond the threshold of 139 AU after incurring eight injuries over the course of approximately 14 months, with severities ranging from 4 to 16 days. However, both the severity of injuries and the time between each

event is highly variable, and so this load could be accumulated in an infinite number of ways for each individual player.

In the most recent sports injury model, Meeuwisse et al. (2007) highlighted the need to account for the changing nature of risk factors. The present study is the first to consider the impact of the severity and recency of previous injuries, rather than simply the absence or presence of past injuries, in any athletic population. The injury load variable used in the present analysis was able to fluctuate, to capture the continually changing risk within each individual (Figure 7.6). The frailty model is able to model such time-varying covariates, and so this strategy should help to account for the changing nature of sports injury risk. In comparison, the variable describing the number of previous injuries a player had incurred could only increase in a sequential fashion, and so was not able to capture the changing risk through time, as evidenced by the substantially poorer model fit when this variable was included in place of the injury load variable. Therefore, the injury load variable was preferable for assessing the impact that previous injuries have upon current injury risk in this population.

The number of matches played in the preceding 30 day period was not a substantial predictor of overall injury risk. Evidence from professional football cohorts suggests that congested fixture periods can lead to fatigue and an increased risk of both injury and poor performance in the ensuing period (Dellal et al., 2013; Dupont et al., 2010). The direct contact between players during Rugby Union matches, in addition to the high physiological demands of the sport (Roberts et al., 2008), are likely to prolong the time-course to full recovery following a match (Gill et al., 2006), and thus makes playing more than two Rugby Union fixtures within a week more difficult in comparison with football and other team sports that do not involve high levels of player-to-player contact. The results of the present study suggest that the current fixture schedule in elite Rugby Union (with matches separated by 6-8 days) is not associated with an increased risk of injury. The reduction in non-contact injury risk for those with high month match load values (greater than median value), as revealed by the subset analyses, may be indicative of the preventative effect of developing high levels of match-specific fitness on these types of injuries. For example, professional Rugby League players with well-developed prolonged high-intensity

intermittent running ability were shown to have a reduced risk of injury (Gabbett et al., 2012a). These results suggest that players who have had a low level of recent match exposure, perhaps through injury or non-selection, should be returned to an appropriate level of conditioning, in a graduated manner, before returning to full match play.

The present study provides novel evidence for there being both within-team and within-player clustering of injury survival times in elite Rugby Union players, and so supports the use of the nested frailty model for the analysis of this recurrent sport injury data. The within-player clustering confirms that injury survival times are correlated via a common risk factor or injury mechanism to which the individual is exposed (Cook, 2010). The within-team clustering of observations may be indicative of the injury risk associated with a given team's training and match practices, the nature of their reporting practices, or both. The frailty model has previously been identified as the most appropriate survival model for sports injury recurrent events (Ullah et al., 2012). The advantages of the frailty model include the fact that it makes fewer statistical assumptions than other common extensions of the Cox PH model, and is able to model time-varying covariates (Haertung, 2011). Future studies investigating risk factors for injury within recurrent sport injury data should use the frailty model ahead of the Cox Proportional Hazards model, in order to appropriately account for clustered survival data.

A limitation of the current study is the lack of individualised training exposure for this group. Whilst the majority of players within a given team are likely to undertake a similar volume of training each week, as assumed in the present study, this may not be true for all players (e.g. players rehabilitating from injury). Moreover, measures of training load, which combine both the intensity and duration of training practices, were not available over the current study period but would be useful for determining the acute and chronic effects of training practices on injury risk. The relationship between training loads and injury risk will be explored in Chapter 8. Future studies with both objective markers (e.g. creatine kinase concentrations) and subjective measures (e.g. player questionnaire data) of fatigue may help elucidate the relationship between fatigue state and injury risk in this population. Additionally, the inclusion of psychological predictors (e.g. trait anxiety, negative-life-event stress and

daily hassle) may help in further understanding the complex association between fatigue and injury risk (Ivarsson et al., 2013). Finally, the injury load variable used in the present study may be developed, in order to fully understand the manner in which previous injuries modify current injury risk (e.g. by considering the injury load incurred at each body site).

7.4.1 Conclusion

In conclusion, the results of the present study demonstrated that high previous injury loads and playing a high number of matches in the preceding season are overall risk factors for injury in this population, while high month match loads were associated with a reduced risk of non-contact injuries. In light of these findings, a reduction in the current match load limit for English professional players may be considered, as a possible means of reducing injury risk in this population. The present study also provided novel evidence for there being both within-team and within-player correlation between injury survival times in elite Rugby Union players, and so supports the use of the nested frailty model for recurrent sport injury data of this nature. These data can be used to identify players at an increased injury risk, so that appropriate interventions can be made to alleviate the risk and prevent the occurrence of injury.

CHAPTER EIGHT

The Development and Application of Injury Prediction Models in Elite Rugby Union

PART ONE: A Machine Learning Model for Predicting Injury Severity

8.1 Introduction

Within professional sport, an estimation of the time to return-to-play is made for every athlete injury, and is one of the most challenging aspects of a sports clinician's role. For coaching staff, this estimation is required to make appropriate tactical changes to the team during the player's expected absence. For the injured player, having an estimated return-to-play date will enable them to prepare for the time course of rehabilitation. Typically, return-to-play predictions are based upon the experience of medical staff, alongside guidelines within the literature (e.g. McCrory et al., 2013; Mendiguchia and Brughelli, 2011; Bizzini et al., 2012). However, it has been proposed that an ethical dilemma exists when medical staff employed by the club are involved in the return-to-play decision, as such decisions may be influenced by short term interests (Fuller and Walker, 2006). Furthermore, the return-to-play decision may also be indirectly influenced by those lacking appropriate medical training, such as coaches, teammates, family members, sponsors, media, fans and team administrators (Beardmore et al., 2005; Creighton et al., 2010).

A high proportion of recurrent injuries in elite sporting populations occur within two months of return-to-play (42-93%) (Chapter 5; Häggglund et al., 2007; Häggglund et al., 2009a; Häggglund et al., 2009b), suggesting that premature return-to-play may have occurred in at least some of these cases. Early recurrences may expose the clinician to direct blame, and so clinicians may therefore be inclined to make more conservative return-to-play decisions in an attempt to avoid such early recurrences. Whilst overly conservative return-to-play decisions are less likely to invoke blame for the clinician, they may adversely affect a team's performance, as players will be unnecessarily unavailable for selection (Chapter 4). As such, the development of additional objective markers to aid clinicians as decision support tools when predicting return-to-play may be helpful.

Machine learning is a field of statistics that develops predictive models which can improve their output with experience (Anderson et al., 1986). Machine learning techniques have been used in a number of sporting applications to predict performance (Bahadorreza et al., 2013; Edelman-Nusser et al., 2002). More recently, Kampakis (2013) used machine learning methods (support vector machines, Gaussian processes and neural networks) to predict the recovery time of professional football players after an undiagnosed injury, using predictor variables such as the stage of the season (e.g. mid-season or off-season), the event leading to injury (e.g. running or shooting), the onset of the injury (acute or gradual-onset), a simple injury diagnosis (e.g. 'bone injury') and the injured player's characteristics (e.g. age and playing position). The model displayed a low degree of accuracy when predicting unseen observations ($R^2=0.13-0.15$; root mean square error [RMSE] in severity prediction = 31.8-32.5 days), with no method performing significantly better than the others. However, the small number of cases ($n = 152$) and lack of injury diagnostic information likely limited the model's prediction capacity. The England Professional Rugby Injury Surveillance Project contains thousands of injury cases recorded with methodological consistency across all studied seasons (2005-2014), and so provides a suitable platform with which to develop and test a machine learning model to predict injury severities. Accordingly, the aim of this study was to develop a machine learning model to predict the severity of injuries incurred by professional Rugby Union players, and to compare the predictive accuracy of this model against return-to-play estimations made by medical staff.

8.2 Methods

8.2.1 Study design and setting

An eight season prospective cohort design (as per Chapter 5) was used to record all match and training injuries associated with elite Rugby Union players at 15 English Premiership clubs, according to agreed protocols as part of the Professional Rugby Injury Surveillance Project (PRISP). Injury and exposure data were returned to a study investigator at the academic host institution of the PRISP (2005-2011, Nottingham University; 2011-2013, University of Bath). Data collected between the 2005/06 and 2012/13 seasons were collated as part of this Ph.D. This injury database was upheld by the academic host institution of the PRISP. In addition, data collected during the 2013/14 season were used to validate the predictive accuracy of the model.

8.2.2 Participants

All consenting players that were members of clubs' first team squads were eligible for inclusion in the study. Data pertaining to a total of 1555 elite Rugby Union players were included in the analysis. The study was approved by the research ethics committee of the academic host institution where the PRISP was based for each season, and written informed consent was obtained from each participant. All data were anonymised.

8.2.3 Variables

The definitions and procedures used in this study were consistent with the international consensus statement for epidemiological studies in Rugby Union (Fuller et al., 2007c). The injury definition used in this study was:

‘Any physical complaint sustained by a player during a first-team match that prevented the player from taking a full part in all training activities typically planned for that day, and/or match play for more than 24 hours from midnight at the end of the day the injury was sustained’.

Injuries incurred during the period 2005/06 to 2012/13 were recorded by medical staff at each club using a modified OSICS system (Orchard, 1995) and standard injury report form. Injuries recorded during the 2013/14 season were entered into ‘The Rugby Squad’ medical database by team medical staff (The Sports Office UK,

2011), according to agreed protocols. Medical staff provided an estimated return-to-play date at the time of recording each injury within the medical database. Each injury was assigned to a bespoke diagnosis grouping based on its three-level Orchard code (Brooks et al., 2005a). Further variables included in the predictive model were: the activity in which the injury occurred (match/training); injury onset (acute or gradual-onset); a variable indicating whether the player was removed from play immediately/delayed/not at all; the player's previous injury load (as described in Chapter 7); a subsequent injury definition (index, new, local, or recurrent, as described in Chapter 5) and the players' position, age, mass and height. The dependent variable was the severity of each injury (days absence from training and match-play). Injuries resulting in less than seven days absence were not included in the analysis, as return-to-play estimations would typically not be required for such minor cases.

8.2.4 *Statistical methods*

All analyses were made using the *party* package with R (version 3.0.3, R Foundation for Statistical Computing, Vienna, Austria). The *cforest* function was used to implement random forest and bagging ensemble algorithms on the dataset. Random forests methods have previously been demonstrated to be useful for predictive tasks (Wu et al., 2009). Moreover, the algorithm runs efficiently on large data sets and can handle unbalanced and missing data effectively (Breiman, 2001a). Briefly, random forests consist of a large number of randomly constructed decision trees, each of which 'votes' for a class or value based on the input vector (Breiman, 2001b). Each decision tree is constructed from a bootstrapped sample of the training data set, and a random selection of the input variables is searched to find the best split at each node (Breiman, 2001b).

The predictive accuracy of the machine learning model was tested on an independent data set (2013/14 season injury data). A spreadsheet was used to assess the predictive accuracy of the model (observed vs predicted severities) using linear regression techniques (Hopkins, 2000). Data were log transformed to improve non-uniformity of error. Additionally, the percentage of predictions that were within 30% of the observed injury severity was used as a more simplistic and practically relevant measure of overall model performance. To compare the accuracy of the predictive

model to a real-world setting, estimated return-to-play dates provided by medical staff at the time of injury registration were assessed for predictive accuracy against observed return-to-play dates using the same methods used to evaluate the machine learning model. These estimations were provided for the same set of injuries used to validate the machine learning model, and were made by medical staff at the time of recording each injury within the medical database. Measures of predictive accuracy produced by the machine learning model and medical staff estimations were compared, and deemed to be substantially different if the 90% confidence intervals (CI) for the variables did not overlap.

8.3 Results

In total, 5129 time-loss injuries were used to train the machine learning model. A total of 399 injuries from the 2013/14 season were used to validate the model. Measures of predictive accuracy from both the machine learning model and medical staff estimations are presented in Table 8.1. Figure 8.1 displays the machine learning model predicted severities versus the observed severities (in part A), and predicted values (from linear regression) versus residual values (in part B). The same plots are presented for medical staff estimations in Figure 8.2. Overall, medical staff estimations were substantially better than the machine learning model predictions of return-to-play across all measures of predictive accuracy.

Table 8.1 Measures of predictive accuracy from machine learning model and medical staff estimations, with 90% confidence intervals

Measure of predictive accuracy	Machine learning model		Medical staff estimations	
	Estimate	90% CI	Estimate	90% CI
Mean bias [%]	-5.2	-10.8 to 0.5	3.3	-1.7 to 8.5
SD of bias [%]	190.0	173.5 to 209.9	125.8	115.9 to 137.5
Typical error of estimate [as a CV %]	105.4	97.5 to 114.9	70.4	65.5 to 76.1
Pearson correlation	0.50	0.43 to 0.56	0.78	0.74 to 0.81
Bland-Altman 95% limits of agreement [days]	80.0		51.8	
Predictions within 30% of observed severity [%]	35.6	30.9 to 40.5	72.7	68.0 to 76.9

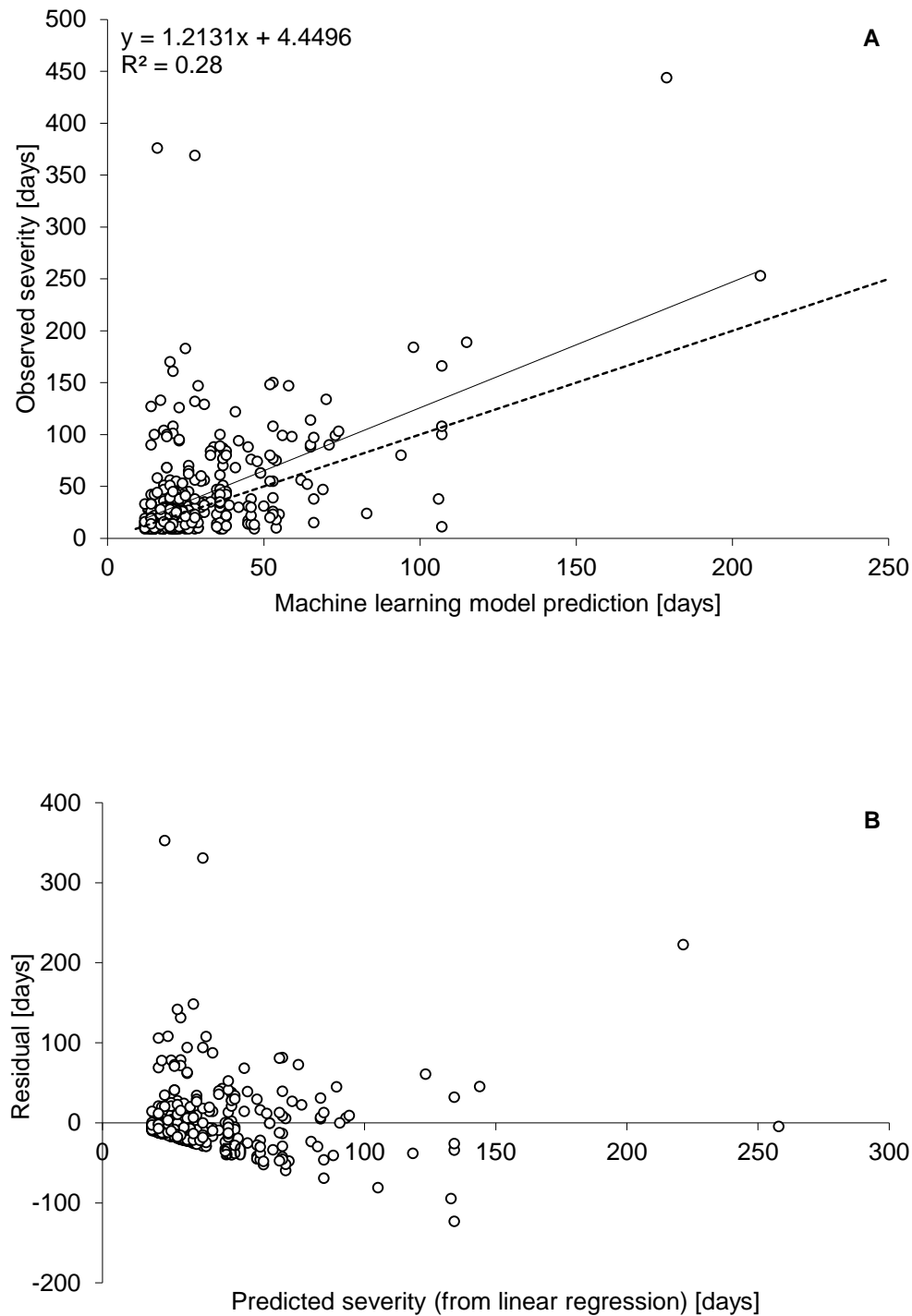


Figure 8.1 Machine learning model predictions vs. observed severities [A] and predicted severities (from linear regression) vs. residual values [B] of 2013/14 season data. Dashed line is line of identity.

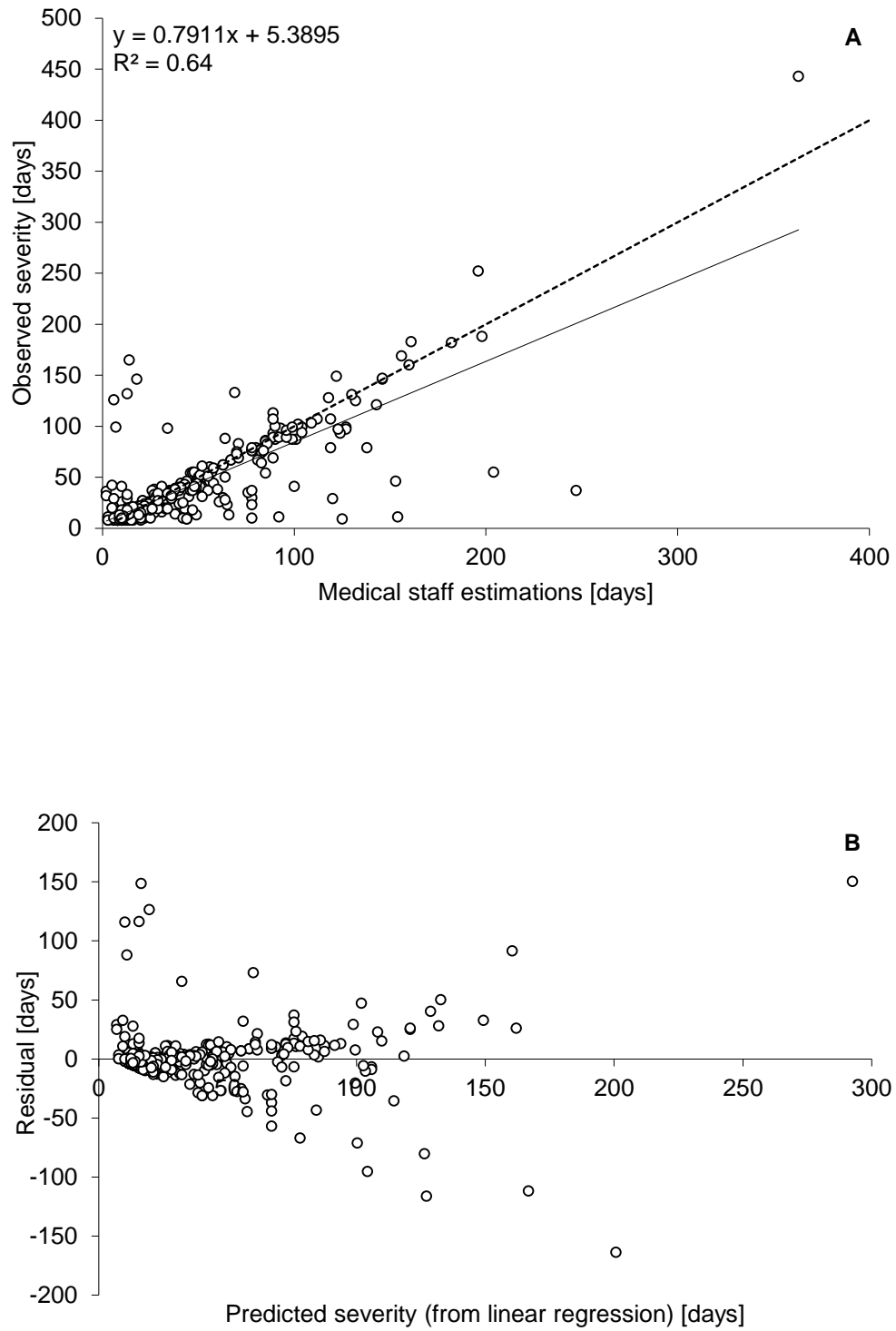


Figure 8.2 Medical staff estimations vs. observed severities [A] and predicted severities (from linear regression) vs. residual values [B] of 2013/14 season data. Dashed line is line of identity.

8.4 Discussion

The current study assessed the predictive accuracy of a machine learning model for estimating the severity of injuries based on a number of predictor variables. The model demonstrated a low degree of predictive accuracy, and performed substantially worse than estimations of return-to-play made by medical staff. As such, the presented machine learning model would not currently be recommended for use within an applied setting.

The low degree of predictive accuracy achieved by the machine learning model in the present study, alongside the similar results obtained by Kampakis (2013) in a professional football population, suggests that such models currently have limited efficacy for predicting the severity of sporting injuries. The predictive accuracy of the machine learning model may be improved with the addition of further predictor variables. For instance, the results of diagnostic or functional tests undertaken shortly after incurring a given injury would likely improve the degree to which the model could differentiate between mild and severe instances of an injury diagnosis. Additionally, the inclusion of psychological predictors (e.g. trait anxiety, negative-life-event stress and daily hassle) may also add predictive value to the model (Ivarsson et al., 2013; Lavalley and Flint, 1996). However, as such data has not been collected to date, several additional seasons of data collection would be required before a suitable machine learning model could be trained using such variables. Moreover, the inclusion of these variables would likely add considerable burden to the data collection process, and so would only be worthwhile if substantial improvements to the predictive accuracy of the machine learning model could be achieved.

The three-step decision-based return-to-play model proposed by Creighton et al. (2010) highlights the numerous factors that clinicians consider (consciously or subconsciously) when making return-to-play decisions. Specifically, step one involves the evaluation of the health status of the athlete (e.g. symptoms, laboratory tests, physical examination, functional tests); in step two, the clinician considers the risk associated with participation (e.g. type of sport, position played, ability to protect the injury) and step three involves accounting for ‘decision modifiers’ (e.g. pressure from athlete, external pressures, fear of litigation) and is the final step in the

process leading to a return-to-play decision. This process is recursive, such that the evaluations are revisited as the rehabilitation progresses. All return-to-play decisions will be strongly influenced by the risk-benefit considerations outlined in step three. For instance, returning a key player for an important play-off fixture may be deemed acceptable (due to the potential rewards associated with winning the match), whereas the risk-benefit balance associated with returning the same player for a less important fixture may not be deemed acceptable. Whilst many of the variables associated with steps one and two of the decision-based return-to-play model may be measured and included within a machine learning model, the ‘decision modifiers’ described in step three are extremely difficult (or impossible) to quantify. The variability introduced by such unmeasured covariates may preclude machine learning models from producing predictions that would be useful in a practical setting. As such, there may be an upper threshold associated with the ability of such models to ‘learn’ from past examples in this context.

During the 2013/14 season, medical staff estimations of return-to-play were available for each of the recorded injuries, which allowed the accuracy of the machine learning model to be compared to a real-world setting. Medical staff estimations of injury severities were shown to be accurate, with 73% of predictions being within 30% of the observed injury severity. The mean injury severity during the study period was 23 days, and so the majority of medical staff estimations of return-to-play for such injuries would be within a week of this value. The positive mean bias reported suggests that medical staff tend to overestimate the severity of injuries (on average). Conservative estimations may be less likely to invoke blame for the clinician, as cases where players return to participation earlier than expected may be viewed as a ‘successful rehabilitation’ in comparison with those that return to participation later than initially predicted. Given the observed accuracy of medical staff estimations, future machine learning models could include these estimations as a predictor variable, to determine whether the combination of these two elements (i.e., the medical practitioner’s estimation and information ‘learnt’ by the model from past instances) could result in an improved overall prediction. This will be feasible once additional medical practitioner estimation data has been collected (at present, such data were only available for the 2013/14 season).

The model presented in the current study may have a greater utility in a community/amateur setting, where medical staff are likely to have less experience than those in the professional game, and so may possess a greater requirement for an injury severity prediction tool. All of the included predictor variables would be readily available in this setting in England via the community rugby injury surveillance project (Roberts et al., 2013), with the exception of the player's previous injury load, which would require computation (but may not necessarily contribute strongly to the predictive accuracy of the model in this setting anyway). Clearly, the model would need to be trained on an appropriate dataset, but it may be argued that such a setting would have a greater necessity for such a tool.

A limitation of the current study is that medical staff would likely have had a strong influence over the final return-to-play decision. Given that the predictive accuracy of the machine learning model was compared with medical staff estimations, the results may therefore be biased in favour of the medical staff. Thus, a comparison between the predictive accuracy of the machine learning model and estimations made by independent medical staff (i.e., ones that do not influence the final return-to-play decision) may be preferable. Moreover, there is no evidence to confirm that the observed injury severities were 'correct' (i.e., some may have been overly conservative or overly aggressive). Objective criterion against which to assess a player's readiness to return to play exists for some injuries. For example, an active hamstring flexibility test (Askling et al., 2010) may be used to determine a player's readiness to return to sport after a hamstring injury, whilst there is a graduated return-to-play protocol following concussion injuries (McCrory et al., 2013). A machine learning model that is trained upon objective clinical testing measures of readiness to return-to-play may be of greater use in aiding medical staff than one that is trained upon severities that have been influenced by the aforementioned decision modifiers. Such a model may be able to provide medical staff with a baseline estimate of return-to-play, founded upon step one and two of the decision-based return-to-play model (Creighton et al., 2010), to which they can apply their decision modifiers. The development of further objective markers and tests for determining return-to-play is required before such a model could be developed.

8.4.1 *Conclusion*

Part one of this chapter evaluated the predictive accuracy of a machine learning model for estimating the severity of injuries in elite Rugby Union. The overall predictive accuracy of the machine learning model was low, and was substantially poorer than estimations made by medical staff. This machine learning approach was likely constrained by the absence of predictor variables that adequately distinguished the severity of a given injury diagnosis; the addition of such predictor variables (e.g. baseline diagnostic/functional tests, medical staffs' own estimations) and a larger training data set may improve the predictive accuracy of the model. Subsequent to improvements being made to the predictive accuracy of the machine learning model, such a tool may have utility in providing an objective estimation of injury severity, to which medical staff can apply relevant 'decision modifiers'. At present, machine learning techniques do not appear to be of practical use for predicting the severity of injuries within an elite sports setting.

PART TWO: An Investigation of the Relationship Between Training
Load Measures and Injury Risk in Elite Rugby Union Players

8.5 Introduction

The aim of training activities is to optimise performance through the mastery of sport specific skills and through the attainment of peak physical conditioning (Killen et al., 2010). Monitoring of training loads is therefore crucial for ensuring that prescribed training and recovery periods optimise performance, without increasing injury risk to an unacceptable level (Gabbett, 2010). The principle of training can be simplified to a dose response relationship, whereby a ‘dose’ of training results in a measureable ‘response’ to a physiological or performance measure (Rhea et al., 2003). The Banister impulse-response model quantitatively relates an athlete’s performance ability at a given time to the cumulative effects (fatigue and fitness) of prior training loads (Calvert et al., 1976). Increasing training loads (a product of the intensity and duration of training sessions) is generally thought to improve athletic performance (Foster et al., 1996), but may also place players at an increased risk of overtraining and injury (Gabbett and Jenkins, 2011). Thus, the prescription of optimal training loads requires a careful consideration of the positive (fitness) and negative (fatigue and injury risk) response elements.

Training loads have been identified as an easily-modifiable risk factor for injury in collision sports. In professional rugby league players, training load was significantly related to overall injury rates ($r=0.82$) (Gabbett and Jenkins, 2011). In Australian footballers, larger ‘one weekly’, ‘two weekly’ and ‘previous to current week changes’ in training load were all significantly related to a larger injury risk (Rogalski et al., 2013). Three-weekly cumulative loads derived from GPS measurements were also found to be associated with an increased risk of injury in this population (Colby et al., 2014). These findings indicate that both the pattern of change and cumulative effect of training loads may be associated with injury risk, in addition to the absolute weekly or daily training load value. Further training load measures include ‘training monotony’, which describes the variation in training loads across a week, and ‘training strain’, which is the product of training monotony and weekly load (Foster, 1998), although neither have been explored in elite

collision sport cohorts. Moreover, an ‘exponentially-weighted moving average’ variable (Kara, 2013) and a ‘training-stress balance’ variable (Hulin et al., 2014) have both shown promise as predictors of injury, but have received limited attention in the literature. No studies have investigated the relationship between training loads and injury risk in elite Rugby Union players hitherto.

Many of the aforementioned training load measures are likely to be correlated (e.g. one, two, three and four weekly cumulative loads); including all of these measures within analyses is therefore not advisable for statistical reasons (Hair et al., 2009). Thus, the reduction of these factors to the most parsimonious set of variables, which still convey the underlying dimensions of the data, would be desirable.

Gabbett (2010) presented an injury risk prediction model for non-contact, soft-tissue injuries in elite Rugby League players. Specifically, the relationship between training load and injury risk was modeled via logistic regression over the course of two seasons. Subsequently, an injury prediction model based on planned and actual training loads was developed, with injury prevalence calculated as the proportion of players injured when actual training loads exceeded planned training loads by a moderate amount (effect size = 0.5). The model was shown to be both sensitive (87%) and specific (99%) for the prediction of non-contact, soft-tissue injuries in this cohort. As such, an injury risk prediction model of this nature could help to provide quantitative support to the ‘intuition and gut feel’ typically used by strength and conditioning personnel when prescribing training loads in collision sports. However, this model only explored the acute effect of training loads (i.e. daily training loads) on injury risk, and did not investigate training load measures that describe the cumulative load placed on players, or changes in training loads (e.g. previous to current week changes). Also, the potential delay between periods of high workloads and subsequent injury in the ensuing period, which may be up to four weeks (Orchard et al., 2009), was not considered. What is more, the repeated observations made across players over the course of the study (i.e. training load values and an injury status indicator was recorded weekly for each player) were likely to have been correlated within individuals (Littell et al., 1998). The logistic regression model used by Gabbett (2010) necessitates that all observations are independent of one another;

violation of this assumption may result in invalid inferences (Kuss, 2002). As such, the statistical method used by Gabbett (2010) may not have been appropriate.

In light of the limitations associated with extant literature in this area, along with the dearth of studies using elite Rugby Union populations, the purpose of this study was to explore the association between training load measures and injury risk in elite Rugby Union, and develop an injury risk prediction model that may be used to predict (and prevent) the occurrence of injuries in this setting. Specifically, the aims of this study were to (a) identify the most pertinent training load measures; (b) explore their relationship with injury risk, and (c) develop and evaluate an injury risk prediction model for use in this population.

8.6 Methods

8.6.1 Study design and setting

This study consisted of (a) the collection of training load and time-loss injury data from one English Premiership team throughout the 2013/14 season; (b) a Principal Component Analysis (PCA) to identify the most pertinent training load measures; (c) the modelling of the relationship between these variables and injury risk using generalised linear mixed modelling methods; and (d) the development and a validation of an injury risk prediction model over the pre-season period of the 2014/15 season.

8.6.2 Participants

Initially, four teams provided training load data throughout the 2013/14 season. However, two of these teams did not provide training load data during the subsequent season (one team was relegated from the English Premiership; the other did not provide the data in sufficient time), and so were excluded from the analyses. Of the two remaining teams, one reported a low number of injuries during the validation phase ($n=4$), such that the additional predictive power associated with the inclusion of this team was negligible. As such, it was decided to only include data for the remaining team. In total, data pertaining to 44 professional Rugby Union players were included in the analyses. The characteristics of the participants (mean \pm SD) were: age, 26 ± 4 y; body mass, 105 ± 14 kg; height, 186 ± 8 cm. Of the 44 players, 35 were included in the validation of the injury prediction model during the 2014/15 pre-season period. The study design and data collection procedures were approved by the Research Ethics Approval Committee for Health at the University of Bath. Written informed consent was obtained from all players included in the study, and all data were anonymised.

8.6.3 Variables

Quantification of training loads

The intensity of each training session a player participated in was estimated using a modified rating of perceived exertion (RPE) scale (Foster et al., 2001). The intensity estimates were obtained approximately 30 minutes after the end of each training session. Training load was quantified by multiplying the training session intensity by the duration of the session (in minutes), to give a load in arbitrary units (AU). The

session RPE method has previously been shown to provide reliable and valid estimations of training intensity in collision sport athletes (Gabbett, 2010); the intraclass correlation coefficient for test-retest reliability and typical error of measurement for the RPE scale were reported to be 0.99 and 4.0%, respectively, whilst correlations between session RPE and physiological markers such as blood-lactate concentration and heart rate were 0.86 and 0.89, respectively. Thus, the session RPE method was an inexpensive, simple and highly practical approach that allowed valid and reliable measures of each player's internal response to training sessions (Clarke et al., 2013).

Training load measures

From the daily training load values described above, a number of training load measures were calculated, as described in Table 8.2. The training load measures were identified from previous investigations of the relationship between training load and injury risk in collision sport athletes, and were included in a PCA to determine the key underlying components of the training load measures. An f value of 0.10 was adopted for the calculation of the exponentially-weighted moving average of training load, based upon a previous study using a comparable population (Kara, 2013).

Table 8.2 Summary of training load measures investigated within the current study, including their calculation and use in extant literature

Training load measure	Calculation	Supporting literature
Daily training load	Session RPE x session duration [minutes]. Where multiple sessions were undertaken on a given day, the loads associated with each session were summed to give daily training load	Gabbett (2010)
1,2,3,4 weekly cumulative loads	Sum of previous (7,14,21,28) day's load values	Rogalski et al. (2013)
Week-to-week change	Absolute difference between current and previous week's training load totals	Rogalski et al. (2013)
Training monotony	A measure of the day-to-day variability of a player's training load within a given week: daily mean/standard deviation	Foster (1998)
Training strain	Weekly training load x training monotony	Foster (1998)
Training stress balance	Calculated by dividing a player's acute workload [one-week load] by their chronic workload [four-week rolling average]	Hulin et al. (2014)
Exponentially-weighted moving average	$f \times$ (previous day's training load) + $(1-f) \times$ (cumulative load up to that point), where f is a decay factor with value between 0 and 1	Holt (2004); Kara (2013)

Time-loss injuries

The injury definition used in this study was: ‘Any physical complaint sustained by a player during a first-team match or training session that prevented the player from taking a full part in all training activities typically planned for that day, and/or match play for more than 24 hours from midnight at the end of the day the injury was sustained’. All injuries were recorded by medical staff at each club using ‘The Rugby Squad’ medical database (The Sports Office UK, 2011), according to agreed protocols. For each day in the included study period, a variable indicating whether the player sustained an injury in the subsequent three week period was included, to account for the potential delay between periods of inappropriate workloads and increased risk of injury (Orchard et al., 2009). The season was split into three phases; pre-season (11 weeks); early-competition (18 weeks) and late-competition (18 weeks). This was undertaken to account for differences in training objectives across these phases, and the likely concomitant variation in the relationship between training load measures and injury (Gabbett, 2010).

8.6.4 Statistical methods

Differences in average weekly training loads between the pre-season, early-competition and late-competition phases were assessed using Cohen’s effect sizes, and were interpreted with the following scale; <0.2, trivial; 0.2 to 0.6, small; 0.6 to 1.2 moderate; and >1.2, large (Hopkins et al., 2009a).

Principal component analysis

A PCA was undertaken to identify logical combinations of the ten training load measures. Subsequently, data reduction was achieved by choosing a surrogate representative variable for each identified factor dimension. In cases where several training load measures were highly correlated with a given component (factor loading > 0.7), a backwards stepwise logistic regression was undertaken using these measures to identify the variable with the largest association with injury risk. Variable importance was assessed based on beta weights and *P*-values (Hair et al., 2009). The PCA was performed using IBM SPSS Statistics for Windows (Version 20.0, Armonk, New York, USA). All data were centered and scaled before conducting the PCA. The Kaiser-Meyer-Olkin (KMO) measure was used to verify the sampling adequacy of the data, with a value of 0.5 used as a threshold for

acceptability (Kaiser, 1974). Bartlett's test of sphericity was also used to determine the suitability of the data for PCA, with significance accepted at an α level of $P \leq 0.05$. Orthogonal rotation (varimax) was used to improve the identification and interpretation of factors (Hair et al., 2009). The optimal number of factors to be extracted was determined by examining the scree plot, Eigenvalue and the 'percentage of variance explained' parameters, alongside a conceptual interpretation of the data structure (Hair et al., 2009). Factor loadings exceeding ± 0.70 were considered indicative of a well-defined structure (Hair et al., 2009).

Influence of training load measures on injury risk

Individual training load measure values and time-loss injury data collected throughout the 2013/14 season were modeled using a generalised linear mixed-effects model, with a binomial distribution and logit link function. This procedure was adopted due to its ability to handle logistic regression, whilst also accounting for clustered and unbalanced data. All estimations were made using the *lme4* package with R (version 3.0.3, R Foundation for Statistical Computing, Vienna, Austria). The results of the aforementioned principal component analysis were used to select the most pertinent training load measures for analysis of their relationship with injury likelihood. In addition to these measures (fixed effects), a random effect for 'player ID' was included to account for the clustered observations within, and heterogeneity between, players (Chapter 7). Estimates were also adjusted for age and grouped playing position. Investigations of quadratic relationships between the training load measures and injury risk were investigated; where evidence of a non-linear relationship was found, the predictor variable was parsed into quartiles (with the lowest range being the reference group) to observe the pattern of injury risk across the full range of values of the risk factor. All continuous predictor variables were log transformed to improve non-uniformity of error. The development of this model provided statistical information concerning the likelihood of injury with a given set of the predictor variables, throughout the different phases of the season (pre-season, early-competition, late-competition).

The log likelihood (LL), Akaike information criterion (AIC) and Bayesian information criterion (BIC) were used to assess, compare and optimise the goodness of fit of the models (Cameron and Trivedi, 2013; Dayton, 2003), with lower values

indicating a better fit to the observed data (Burnham and Anderson, 2004). An effect size, representing the change in injury risk across the range of the predictor variable, was extracted using the *plotLMER.fnc* function in the *LanguageR* package to determine the practical importance of each effect. Effect sizes were interpreted with the following scale: <.11, trivial; 0.11 to <.43, small; .43 to <2.2, moderate; 2.2 to <3.3, large; ≥ 3.3 , very large (Hopkins et al., 2009).

Injury prediction model

The *predict.merMod* function (within the *lme4* package) was used to predict the likelihood of injury for each observation observed during the pre-season phase of the 2014/15 season. A random effect for ‘player ID’ was included in these estimations, to allow individualised predictions to be made based on the relationships observed during the 2013/14 season. Injury prevalence was calculated as the proportion of players injured when the predicted injury probability was greater than 60%; this cut-off value was determined iteratively to provide the best predictive fit (Neter et al., 1989).

Sensitivity and specificity of injury prediction model

To evaluate the predictive accuracy of the injury prediction model, sensitivity and specificity values were calculated using the following equations (Altman and Bland, 1994):

$$\text{Sensitivity} = \frac{\text{True positives}}{\text{True positives} + \text{False negatives}} \quad \text{Eq. 8.1}$$

$$\text{Specificity} = \frac{\text{True negatives}}{\text{False positives} + \text{True negatives}}$$

Whereby ‘true positives’ represent cases (days) where an injury was predicted and the player did sustain a subsequent injury, ‘true negatives’ represent cases where no injury was predicted and the player did not sustain a subsequent injury, ‘false positives’ includes cases where an injury was predicted but the player did not sustain a subsequent injury, and ‘false negatives’ describe cases where no injury was predicted but the player did sustain a subsequent injury. Furthermore, positive and negative likelihood ratios were calculated using the following equations (Deeks and Altman, 2004):

$$\text{Positive likelihood ratio} = \text{Sensitivity}/(100 - \text{Specificity}) \quad \text{Eq. 8.2}$$

$$\text{Negative likelihood ratio} = (100 - \text{Sensitivity})/\text{Specificity}$$

Whereby the positive likelihood ratio represents the ratio between the probability of a positive test result given the presence of a subsequent injury and the probability of a positive test result given the absence of a subsequent injury. Similarly, the negative likelihood ratio represents the ratio between the probability of a negative test result given the presence of a subsequent injury and the probability of a negative test result given the absence of a subsequent injury. Values of 2, 5 and 10 were used as thresholds for ‘acceptable’, ‘good’ and ‘excellent’ positive likelihood ratios, respectively (Deeks and Altman, 2004). For negative likelihood ratios the corresponding boundaries were 0.5, 0.1 and 0.02, respectively. Data are presented alongside 95% confidence intervals.

8.7 Results

8.7.1 *Incidence rate of time-loss injuries during the 2013/14 season*

In total, 13,562 player hours (match, 720; training, 12,842) of exposure and 140 time-loss injuries (match, 89; training, 51) were recorded during the 2013/14 season. This equated to a match injury incidence rate of 123.6 per 1000 player hours (95% CI, 100.4 to 152.2) and a training injury incidence rate of 4.0 per 1000 player hours (95% CI, 3.0 to 5.2). Of the 44 squad members, all but one player sustained at least one time-loss injury. Of the injured players, 38 (88%) sustained two or more time-loss injuries.

8.7.2 *Training loads*

Average weekly training loads across the pre-season, early-competition and late-competition phases are displayed in Figure 8.3. Training loads during the pre-season and early competition phases were substantially greater than the late-competition phase, with effect sizes of 0.28 and 0.24, respectively. Differences between the pre-season and early-competition phases were trivial (effect size = 0.05).

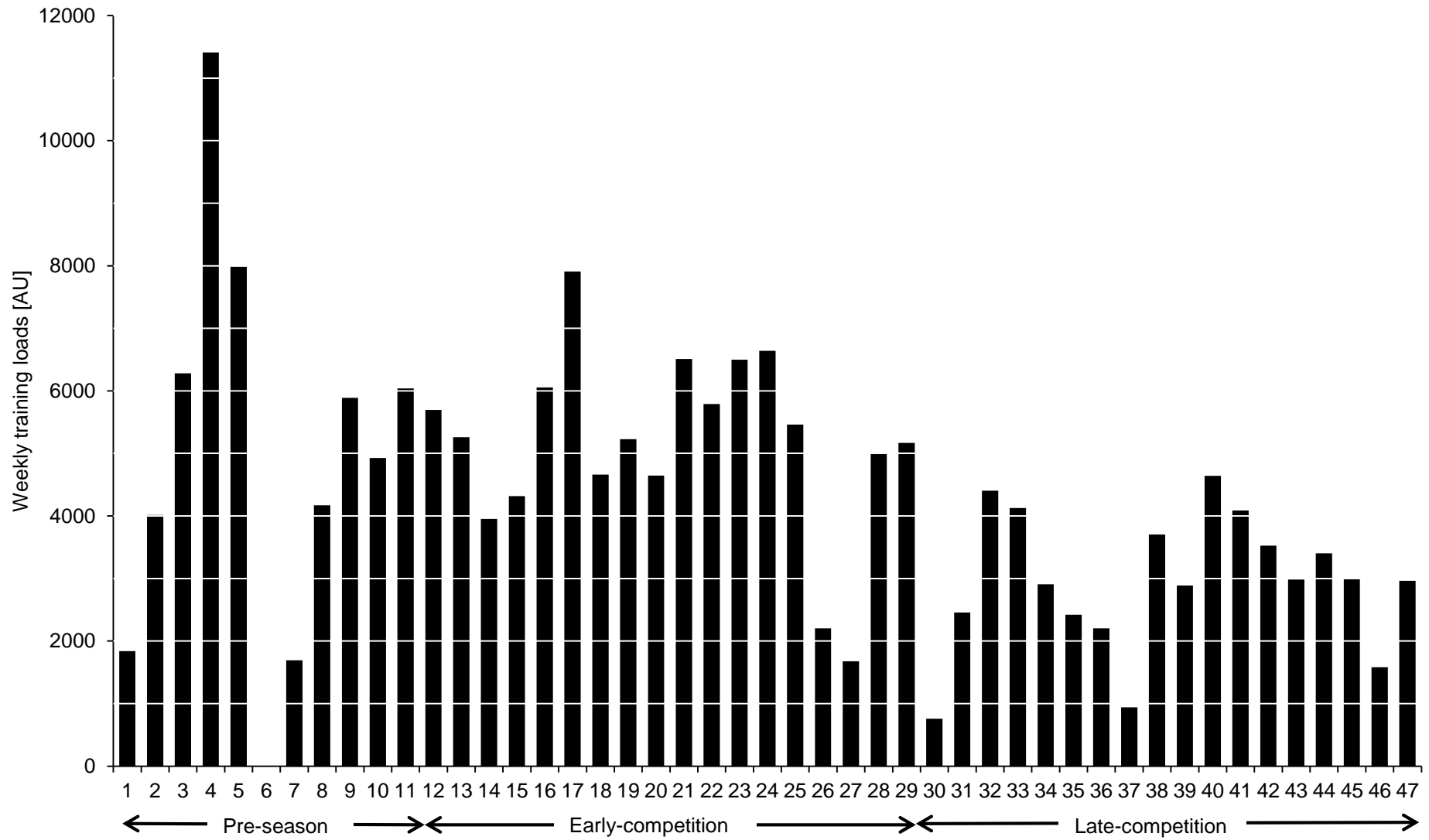


Figure 8.3 Average weekly training loads per player across the three phases of the 2013/14 season.

8.7.3 Principal component analysis

Both the KMO measure of sampling adequacy and Bartlett's test of sphericity indicated that the data were suitable for PCA, with values of 0.74 and $P < 0.001$, respectively. Three components were identified; component one explained 57% of the variance, component two explained an additional 24% of variance, and component three explained an additional 9% of total variance. Overall, the three components explained 90% of total variance. Table 8.3 shows the factor loadings after rotation. The training load measures that cluster on the same components suggest that component one represents measures of the 'cumulative load' placed on players, component two measures 'relative changes in load' and component three is a measure of 'acute load'. The identified dimensions of the training load measures were deemed to have good face validity. Backward stepwise logistic regression analyses were undertaken to select the measure within each component that had the largest association with injury risk (see Appendix; Table A.2 and Table A.3). As a result, component one (cumulative load) was represented by the exponentially-weighted moving average and component two (relative changes in load) was represented by the week-to-week change. Daily training load was the only variable highly correlated with component three (acute load), and so was automatically selected as the representative variable for this component.

Table 8.3 Rotated component matrix of the training load measures

	Component		
	1 [Cumulative]	2 [Relative changes]	3 [Acute]
Daily training load [†]	0.15	0.14	0.98
1 week cumulative load	0.84	0.47	-0.21
2 week cumulative load	0.95	-0.02	0.14
3 week cumulative load	0.94	-0.22	0.12
4 week cumulative load	0.88	-0.34	0.12
Week-to-week change [†]	0.08	0.88	-0.16
Training monotony	0.68	0.47	-0.16
Training strain	0.79	0.50	-0.21
Training stress balance	-0.19	0.86	0.00
Exponentially-weighted moving average [†]	0.98	-0.00	-0.08

Note, factor loadings $> .70$ appear in bold. [†], variable with the highest factor loading in one of the three components.

8.7.4 Influence of training load measures on injury risk

The results of the generalised linear mixed-effects model are displayed in Table 8.4. Evidence of a non-linear relationship was found for the week-to-week change variable only. A substantial relationship between the exponentially-weighted moving average measure and injury risk was evident across all phases of the season. Significant but trivial effects for the week-to-week-change variable were evident during the pre-season and late-competition phases. High daily training load values during the pre-season and late-competition phases were associated with an increased risk of injury, with effect sizes of 0.04 and 0.10, respectively. Changes in the likelihood of incurring a subsequent injury across the range of the training load measures are displayed in Figure 8.4.

Table 8.4 Association between training load measures and injury risk for pre-season, early-competition, and late-competition phases of the season

Training load measure	Odds ratio [Exp(β)]	90% CI	P-value	Effect size
Pre-season				
Exponentially-weighted moving average [AU]	1.38	1.16 to 1.65	0.003	0.23
Week-to-week change [AU]				0.08
<248 (reference)	1.00			
248 to <521	0.71	0.54 to 0.92	0.03	
521 to <911	0.77	0.60 to 0.99	0.09	
≥ 911	0.57	0.44 to 0.73	0.0003	
Daily training load [AU]	1.03	1.00 to 1.07	0.08	0.04
Early-competition				
Exponentially-weighted moving average [AU]	1.63	1.41 to 1.89	<0.001	0.15
Week-to-week change [AU]				0.007
<248 (reference)	1.00			
248 to <521	0.98	0.80 to 1.20	0.86	
521 to <911	1.03	0.84 to 1.26	0.81	
≥ 911	0.96	0.75 to 1.22	0.77	
Daily training load [AU]	1.02	0.99 to 1.05	0.23	0.02
Late-competition				
Exponentially-weighted moving average [AU]	2.36	2.03 to 2.73	<0.001	0.31
Week-to-week change [AU]				0.05
<248 (reference)	1.00			
248 to <521	0.94	0.79 to 1.11	0.53	
521 to <911	0.72	0.60 to 0.88	0.006	
≥ 911	1.07	0.76 to 1.50	0.76	
Daily training load [AU]	1.09	1.06 to 1.12	<0.001	0.10

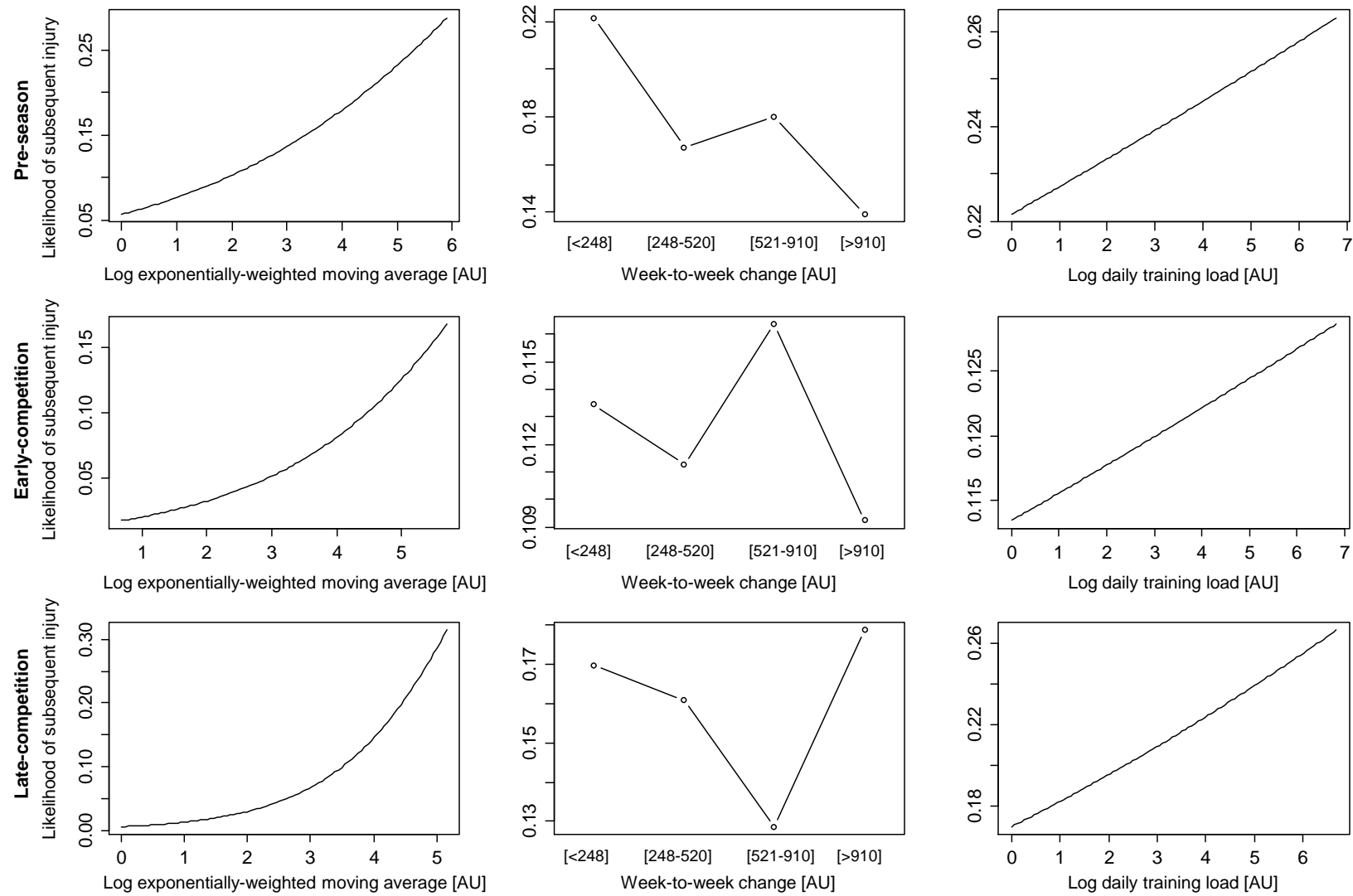


Figure 8.4 Relationship between training load measures and likelihood of injury in pre-season, early-competition and late-competition phases of the season.

8.7.5 Injury prediction model

In total, 27 injuries were sustained during the pre-season period of the 2014/15 season. Of these, 11 were incurred during running/conditioning, 6 were incurred during tackles, 4 were incurred during rucks and mauls, 4 had unknown/unreported inciting events, and 2 were incurred during (accidental) collisions. Of the 35 players included in the validation of the injury risk prediction model, 20 (57%) were injured during the pre-season phase of the 2014/15 season. Of the injured players, five (25%) sustained two or more time-loss injuries. The associated sensitivity and specificity values of the injury prediction model are presented in Table 8.5. The calculated positive and negative likelihood ratios were 2.62 (95% CI: 2.31-2.98) and 0.47 (95% CI: 0.39-0.56), respectively.

Table 8.5 Sensitivity and specificity of injury prediction model

		Actual status	
		Injured	Not injured
Predicted status	Predicted injury	True positive N=142	False positive N=440
	Predicted no injury	False negative N=78	True negative N=1346
		Sensitivity 64.6% (57.8-70.1%)	Specificity 75.4% (73.3-77.4%)

8.8 Discussion

The aim of this study was to identify the most pertinent training load measures in this elite Rugby Union sample, explore their relationship with injury risk, and develop an injury risk prediction model. The PCA characterised three underlying dimensions of the training load measures; cumulative loads, relative changes in loads, and acute loads. Modelling of the relationship between representative variables for each of these dimensions and subsequent injury risk identified the exponentially-weighted moving average variable as having the largest impact on likelihood of injury across all phases of the season. The relationships identified were shown to have an acceptable degree of accuracy in predicting injuries during the subsequent season's pre-season phase, but further refinement is needed before the injury risk prediction model could be implemented within an elite Rugby Union team setting.

The three components identified by the PCA each explained a unique dimension of the training load variable. Component one, which explained the largest proportion of variance (57%), was most associated with training load measures describing the cumulative load that players had been subjected to. The exponentially-weighted moving average measure was chosen as the surrogate representative variable for this 'cumulative load' dimension, and was found to have a substantial association with ensuing injury risk across all phases of the season. It may be that these 'cumulative load' measures describe the accumulation of fatigue within players, which may result in a reduction in the stress-bearing capacity of tissue (Kumar, 2001), and thus an increased likelihood of subsequent injury. Additionally, fatigue effects incurred cumulatively may alter neuromuscular control responses, such that potentially hazardous movement strategies are employed that increase the likelihood of injury (McLean et al., 2007). Cumulative loads should therefore be monitored for individual elite Rugby Union players, as they have a substantial association with subsequent injury risk. These findings also indicate that efforts to improve team performance through the prescription of high training loads may not be advisable, given the observed associations between high cumulative training loads and injury risk, and the impact these injuries may then have upon team success (Chapter 4).

The association between the exponentially-weighted moving average measure and injury risk was greatest during the late-competition phase. This finding implies that during the late-competition phase, lower cumulative loads can be tolerated by players, possibly due to the fatigue effects incurred cumulatively across the whole of the season. Moreover, psychological stress associated with the late-competition phase may reduce the cumulative load thresholds that players can tolerate (Ivarsson et al., 2013).

The second component identified by the PCA was highly associated with the two training load measures that describe relative changes in a player's load (week-to-week change and training stress balance). This component described an additional 24% of total variance. Substantial previous to current week changes in load (>1250 AU) were found to significantly increase injury risk in elite Australian footballers (Rogalski et al., 2013). These results were deemed to be especially pertinent to players returning from injuries; a more conservative approach to the increase in week-to-week training loads for previously injured players was therefore advocated. Elsewhere, elite cricket fast bowlers with a training stress balance of greater than 200% had a relative risk of injury 4.5 times greater compared with those with a training stress balance of 50-99% (Hulin et al., 2014). In the current study, there was a statistically significant, but practically trivial, decrease in injury risk associated with week-to-week changes of greater than 248 AU during the pre-season phase. One reason for these divergent findings may be the fact that the present study considered the risk of injury over the subsequent three week period, as per the recommendation of Orchard et al. (2009), whereas Rogalski et al. (2013) considered 'current' injury risk only. Progressions in training load during the pre-season phase (i.e. week-to-week changes of >248 AU) may elicit positive fitness adaptations that protect players from injury over the subsequent three week period to a small extent. Indeed, Gabbett (2010) noted that prescribing weekly training loads above specified 'injury risk' thresholds (but not excessively so) may be a worthwhile exercise for producing greater physical adaptations and mental durability in players. In light of the findings from the present study, week-to-week changes during pre-season should be managed in the context of each player's cumulative load. Interestingly, a week-to-week change of 521-910 AU was associated with a significant reduction in subsequent injury risk during the late-competition phase, compared with all other

quartiles. Unfortunately, as the week-to-week change variable considered the absolute change in load only, and not the direction of that change, it is not possible to ascertain whether an increase or decrease in week-to-week loads was associated with the observed decrease in likelihood of injury. However, given the presented findings regarding the impact of cumulative loads on injury risk, it is plausible that a moderate week-to-week reduction (i.e. 521-910 AU) in training loads at this stage of the season results in a suitable reduction in players' cumulative loads (and associated fatigue), such that their subsequent injury risk is attenuated.

The third component identified by the PCA only contained one highly-weighted factor, daily training load, which may be considered an 'acute' training load measure. This variable described an additional 9% of total variance. Ensuing analyses revealed statistically significant increases in subsequent injury risk associated with high acute training load values during the pre-season and late-competition phases. The effect size for daily training loads during the late-competition phase (0.10) approached the smallest worthwhile effect threshold (0.11), and so was especially pertinent during this phase of the season. This finding suggests that during the late-competition phase, when fatigue effects incurred cumulatively across the season and psychological stressors may be present, players are less able to tolerate high 'acute' training loads. Specifically, a daily training load value equivalent to two standard deviations above the average daily training load observed during this phase (equivalent to ~500 AU) may be a useful threshold for this team. Decisions to allow players to exert themselves beyond this threshold on a given day could then be made on a case-by-case basis, with consideration given to factors such as the player's age, match load, and importance to the team.

Players that had a predicted probability of injury of greater than 60% during the subsequent season's pre-season phase were 2.62 times more likely to incur an injury in the ensuing three week period, whereas players that did not exceed the threshold were injured 0.47 times as often. These likelihood ratio values suggest the model had a fair (acceptable) efficacy for predicting injuries in this context, and has the potential be a useful tool to assist practitioners in the optimal prescription of training loads. A previous example of an injury risk prediction model in collision sport athletes demonstrated substantially better predictive performance (Gabbett, 2010),

with positive and negative likelihood ratios of 70.0 and 0.1, respectively. The divergent results may be due to several factors; firstly, the total number of injuries used to validate the injury prediction model in the current study ($n=27$) was substantially lower than the number included by Gabbett ($n=159$). Related to this, Gabbett's injury risk prediction model focussed on the prediction of non-contact, soft-tissue injuries, whereas the current study considered all injuries. Non-contact, soft-tissue injuries are more likely to be directly related to excessive training loads, insufficient recovery and overtraining than those that occur during contact events (Gabbett and Domrow, 2007; Gabbett and Ullah, 2012). As such, the potential to predict (and prevent) these types of injuries is likely to be larger. There were an insufficient number of non-contact, soft-tissue injuries incurred over the current validation study period ($n=11$) to allow for such an analysis to be undertaken. A longer period of follow-up would allow for non-contact, soft-tissue injuries alone to be predicted, and would likely improve the predictive accuracy of the model.

As previously stated, a limitation of the current study was its sample size, which precluded specific investigations of non-contact, soft-tissue injuries. Additionally, the results may not be generalisable to other elite Rugby Union teams, for whom divergent training/recovery practices may alter the observed relationships between training loads and injury risk. Moreover, the ability of the model to predict injuries during the competitive phases of the season, and the effects of given training loads from a performance perspective, were not considered. The potential limitations of the PCA approach must also be considered; namely, the assumption that directions (eigenvectors) with the largest variance are of most interest, and that the principal components are orthogonal to one another (Shlens, 2009). Yet, given that the data were tested for its suitability for reduction and the identified components were deemed to have strong face validity, PCA was considered a useful data reduction approach that overcame the limitations associated with traditional stepwise regression techniques (Flom and Cassell, 2007).

Future injury prediction models could incorporate further measures of training load (e.g. global positioning system and accelerometer data), which may be able to provide additional unique information regarding the training load placed on players, such as the number and magnitude of collisions that players have been involved in

(Gabbett, 2010). Moreover, psychological predictors (e.g. trait anxiety, state anxiety, and negative-life-event stress) may be beneficial when determining the players that may be unable to tolerate prescribed loads (Ivarsson et al., 2013).

8.8.1 Conclusion

Part two of this chapter identified three dimensions underlying the numerous training load measures used in extant literature; cumulative loads, relative changes in load, and acute loads. Subsequent analyses showed a cumulative load variable (exponentially-weighted moving average) to have the greatest impact on overall injury risk across all phases of the season. An injury risk prediction model demonstrated an acceptable degree of accuracy when predicting injuries incurred during the pre-season phase of the following season, based on the relationships identified in the preceding season. Improvements in predictive accuracy may be achieved by modelling non-contact, soft-tissue injuries only, as these are likely to be more closely associated with excessive training loads, insufficient recovery and overtraining than injuries incurred during contact events. Continued collection of training load data in this population will therefore be required. These findings provide novel information regarding the association between training load measures and injury risk across different phases of the season, and demonstrate the potential efficacy of an injury prediction model for guiding the optimal prescription of training loads in this setting.

8.9 Overall chapter summary

This chapter investigated techniques to predict both the occurrence and severity of injuries in elite Rugby Union players. Neither element was predicted to a degree of accuracy that would currently be of practical benefit within an elite sports setting, although both models demonstrated potential for application with larger data sets in the future.

CHAPTER NINE

Discussion

9.1 Introduction

The aim of this thesis was to investigate risk factors for injury in elite Rugby Union players. A number of novel research questions were formulated in Chapter 1 in order to achieve this aim, and those research questions were subsequently addressed in Chapters 3-8 of this thesis. The aim of this chapter is to provide a summary of the main research findings of the thesis, and discuss the extent to which the proposed research questions have been addressed. In doing so, the degree to which these findings have produced an original and significant contribution to existing knowledge will be highlighted. Additionally, a discussion of the strengths and weaknesses of the adopted methodological approach underlying this work is provided, the potential practical implications are explored, and recommendations for future research in this area are proposed.

9.2 Addressing the research questions

The publication of a consensus statement for studies of injuries in Rugby Union in 2007 (Fuller et al., 2007c) has resulted in an improvement in the methodological quality and consistency of research in this area. As such, it was possible to systematically collate and summarise this work, to provide a full and precise understanding of the magnitude of the injury problem in elite Rugby Union (as outlined in step one of van Mechelen's 'sequence of prevention' model). This led to the formulation of the first research question:

- i. What is the overall level of injury risk within elite Rugby Union, and which facets of the game carry the greatest risk?**

Key Findings:

- Overall match incidence rate was 81 per 1000 player hours, with mean severity of 20 days.
- Overall training incidence rate was 3 per 1000 player hours, with mean severity of 22 days.
- Recurrent injuries were typically 10 days more severe than new injuries.

- Joint (non-bone)/ligament injuries and lower limb injuries had the highest injury burden for injury group and body region, respectively.
- The first quarter (0-20 min) of matches had the lowest injury incidence rate, and the tackle was the most common inciting event.

The overall risk of injury within elite Rugby Union is therefore high in comparison to other popular sports. As such, it was desirable to understand how these injuries may be associated with team success. Providing evidence of a substantial association between injury measures and team success may be useful when attempting to communicate the importance of injury prevention to Rugby Union stakeholders, and when striving to implement injury prevention initiatives within this elite sport setting. For this reason, there was a clear need to address the second research question:

ii. Is there an association between injuries and team success in elite Rugby Union?

Key Findings:

- Clear negative relationships were found between injury measures and team success for both within-team changes and between-team differences.
- A within-team change in injury burden of ~42 days per 1000 player hours was associated with the smallest worthwhile change in league points tally (± 3 league points).
- This burden equates to a typical Premiership team reducing the total number of injuries incurred by ~21 injuries per season (in the context of a mean of 83 injuries per team per season), or by reducing the average severity of all injuries by ~5 days (in the context of a mean injury severity of 24 days).

The injury measures analysed in Chapter 4 accounted for both the incidence rate and severity of injuries (i.e. injury burden). Therefore, one possible interpretation of the results is that by using aggressive rehabilitation strategies, players could be returned to play earlier (in comparison with a conservative approach), thus reducing the team's overall injury burden (and potentially improving overall team success). However, the risk of subsequent or recurrent injury following the aggressive rehabilitation must also be considered. A deeper understanding of subsequent

injuries and the risk of early recurrence in this population would therefore be desirable. Additionally, Chapter 3 highlighted the greater severity associated with recurrent injuries in comparison with new injuries, but also noted the absence of studies assessing the severity of injury recurrences in comparison with their associated index injury in Rugby Union. Accordingly, the third research question was developed:

iii. How are subsequent injuries distributed within an elite Rugby Union population, and are there injury diagnoses with an increased risk of early recurrence?

Key Findings:

- A large proportion of recurrent injuries (42%) occurred within two months of return-to-play, with specific injury diagnoses (relating to the neck, ankle and hip flexors/quadriceps) identified as having a higher risk of early recurrence.
- Contrary to existing assumptions, recurrent (as well as local and new) subsequent injuries were not more severe than their associated index injury.

Rugby Union has been traditionally played on natural grass surfaces. However, third-generation artificial playing surfaces have recently been introduced to the English Premiership, and their use is expected to increase across all levels of the game in the future. As such, it is necessary to understand how artificial playing surfaces may influence the risk of injury during elite Rugby Union matches, and so determine whether they are an external risk factor for injury in this population. Thus, a prospective cohort study of teams playing matches on artificial turf and natural grass playing surfaces in an elite Rugby Union setting was conducted to answer research question *iv*:

iv. What influence does an artificial playing surface have upon injury risk during elite Rugby Union matches?

Key Findings:

- There were no clear differences in the incidence rate, severity or overall injury burden of time-loss injuries between matches played on artificial turf and natural grass, based on thresholds set to detect moderate effects.

- Abrasions were substantially more common on the artificial surface compared with natural grass. The majority of these were minor, and only two resulted in any reported absence from training or match play.
- Muscle soreness was consistently higher over the four days following a match on artificial turf in comparison with matches played on natural grass, although the magnitude of this effect was small.
- Continued surveillance is required to detect any differences in injury patterns and any smaller difference in overall injury risk.

Previous injury and high match loads have been identified as potential intrinsic risk factors for injury in other sporting populations, but their effects in elite Rugby Union populations have not been investigated. Additionally, the findings presented in relation to research question *iii* highlighted the repeated nature of injury events within this population, alongside the need to account for the heterogeneity in injury risk between players. Accordingly, the fifth research question was proposed:

- v. What influence do previous injury and match loads have upon injury risk in elite Rugby Union players, and is the frailty model an appropriate analysis strategy for this recurrent injury data?**

Key Findings:

- High previous injury loads and playing a high number of matches in the preceding season were overall risk factors for injury in this population.
- Month match loads were not associated with overall injury risk, but high month match loads were associated with a reduced risk of non-contact injuries.
- There was evidence of within-team and within-player correlation between injury survival times, which supported the use of the frailty model in this setting.

The investigations relating to research question *v* revealed that previous injury loads are a risk factor for injury in elite Rugby Union players. Related to this, subsequent injuries are common and the relationships between them are complex (research question *iii*). A premature return-to-play may augment the risk of subsequent injuries, and result in a greater overall injury burden. Equally, overly conservative

return-to-play decisions result in unnecessary absence from training and match-play, which is likely to negatively impact on team success (research question *ii*). In light of these findings, the development of additional objective markers to aid clinicians as decision support tools when predicting return-to-play was desirable. Moreover, the overarching aim of all sports injury epidemiology work is to reduce the burden of injury and improve the welfare of the sport's participants. A recent study involving elite collision sport athletes has identified a readily-modifiable intrinsic risk factor for injury (training load), and subsequently developed an injury risk prediction model that was shown to be efficacious for predicting injury occurrence (Gabbett, 2010). Accordingly, the sixth and final research question was proposed:

vi. Can predictive modelling techniques be used to predict the severity and occurrence of injuries in elite Rugby Union players?

To address this final research question, a study of predictive modelling techniques described in Chapter 8 was undertaken. This chapter consisted of two parts; part one evaluated the efficacy of a machine learning model to predict the severity of injuries in this population, whilst part two presented an investigation of the relationship between training load measures and injury risk, and the efficacy of training load measures in predicting the occurrence of injuries.

Key Finding from Part One:

- The machine learning model demonstrated a low degree of predictive accuracy ($R^2=0.28$), and performed substantially worse than estimations of return-to-play made by medical staff ($R^2=0.64$).
- The model's inability to account for 'decision modifiers' (Creighton et al., 2010) likely limited its predictive capacity.

Key Findings from Part Two:

- Three dimensions underlying the numerous training load measures used in extant literature were identified via Principal Component Analysis; cumulative loads, relative changes in load, and acute loads.
- A cumulative load variable (exponentially-weighted moving average) had the greatest impact on overall injury risk across all phases of the season.

- Players that exceeded an ‘injury prediction probability’ threshold of 60% were 2.62 times more likely to incur an injury in the ensuing three week period, whereas players that did not exceed the threshold were injured 0.47 times as often.
- Further refinement of the predictive models used in parts one and two of this chapter are required before they can be implemented within an elite rugby setting.

9.3 Original contribution to knowledge

Madsen (1983, p.25) described an ‘original contribution to knowledge’ as:

“...the potential to do at least one of the following: uncover new facts or principles, suggest relationships that were previously unrecognized, challenge existing truths or assumptions, afford new insights into little-understood phenomena, or suggest new interpretations of known facts that can alter man’s perception of the world around him.”

To that end, this thesis makes an original and significant contribution to the knowledge by:

- Providing the first meta-analytic data of injuries in elite Rugby Union.
- Highlighting the negative association between injuries and team success in elite Rugby Union.
- Describing the nature and distribution of subsequent injuries in this population and, contrary to existing assumptions, showing that the severity of subsequent injuries is not greater than their associated index injury.
- Providing the first investigation of the influence that artificial playing surfaces have upon injury risk during elite Rugby Union matches.
- Evidencing ‘injury loads’ and ‘previous season match loads’ as intrinsic risk factors for injury in this population, and demonstrating the suitability of the frailty survival model for analysing elite Rugby Union injury data that includes subsequent injuries.
- Detailing the dimensions underlying the numerous training load measures described in extant literature, their relationship with injury risk, and their ability to predict future injuries in this population.

9.4 Discussion of methodological approach

The injury data used throughout this thesis were collected as part of the England Professional Rugby Injury Surveillance Project. A clear strength of these data lies in their size and completeness; each season, injury and exposure data is provided for almost all (~99.5%) of the target population (professional Rugby Union players playing in the English Premiership). In addition, these data have been collected in a methodologically consistent manner since the 2002/03 season, providing a large sample size that now allows sophisticated methods of analysis to be employed with confidence. However, a topic of debate pertinent to all injury surveillance studies is the definition of what constitutes an injury. The injury definition used by the England Professional Rugby Injury Surveillance Project is:

‘Any physical complaint sustained by a player during a first-team match or training session that prevented the player from taking a full part in all training activities typically planned for that day, and/or match play for more than 24 hours from midnight at the end of the day the injury was sustained’.

This definition excludes ‘slight’ injuries (0-1 days absence), as defined within the consensus statement for studies of Rugby Union injuries (Fuller et al., 2007c). It may therefore be argued that a large proportion of ‘injuries’ that occur within professional Rugby Union are not recorded (i.e. ‘medical attention’ injuries and/or those that result in ≤ 1 days absence from full participation). Thus, a complete picture of the epidemiology of injuries in this setting may be lacking. The converse argument at the other extreme is that the reliability associated with the recording injuries of mild severity (less than one week) may be poor, and so definitions that are clear and robust to individual interpretation (e.g. missed match definitions) are preferable (Orchard et al., 2007). For example, cases where a player is regularly unable to participate in the first training session of a week due to a chronic injury that is aggravated during match-play are likely to be common in elite Rugby Union teams. Such cases should technically be recorded as a new injury on the first occasion, and then as an injury recurrence on all subsequent occasions that the player is unable to take a full part in planned training activities. Yet, different recorders may treat this (common) scenario in divergent ways; for some, the training on that day may not be considered as ‘planned’ for that player, if the injury reoccurs regularly and the player

is therefore managed on an individual basis. Others may interpret the ‘start date’ of such chronic injuries differently, or may simply only report the absence from training as an injury during weeks where their schedule allows. These issues highlight the ways in which the reliability of reported time-loss injuries (particularly <7 day injuries) may be affected by the varying degrees of technical adherence to the definitions. However, there are a number of potential limitations associated with the alternative approach of using a missed match injury definition (which is likely to provide a greater level of reliability both within and across teams). Firstly, it may result in a loss of accuracy in some components of data collection (e.g. injury mechanism) if medical practitioners wait until a match has been missed before recording the details of the injury. What is more, injuries that occur during the last match of the season (and so cannot result in the player missing a match) are likely to be missed, whilst further bias is introduced where matches deviate from being separated by seven days (during international periods, or when there are six and eight day turnarounds). Moreover, a substantial proportion of time-loss injuries reported in this setting do not result in players missing a match (~23%). As such, the injury definition used throughout this thesis may be defended on the basis that it captures and describes a substantial proportion of the injuries within elite Rugby Union (in comparison with a missed match definition), without introducing unmanageable burden for medical staff, or the likely variability associated with using ‘tissue damage’ or ‘medical attention’ injury definitions.

Magnitude-based inferences have been used throughout this thesis to make decisions regarding the size and practical importance of observed effects. The frequentist approach to statistical inference is to define results as ‘statistically significant’ if the associated *P*-value (representing the likelihood of obtaining an effect larger than the one observed, if the null hypothesis were true) is less than a threshold value (typically 0.05). Null hypothesis testing remains the dominant approach within exercise science and epidemiology, and is the form of analysis expected and required by many journal editors. Indeed, the continued use of null-hypothesis testing in spite of continued criticisms over the past hundred years implies that the approach must have considerable strengths (or that there are no suitable alternatives) (Frick, 1996).

The magnitude-based inference approach was deemed to be more appropriate for the research questions proposed in this thesis than the traditional null-hypothesis testing method. Firstly, this approach requires the researcher to define the ‘smallest worthwhile effect’, and so considers the practical importance of the effect, rather than relying solely on statistical significance. This is particularly pertinent when large sample sizes are analysed, as was the case throughout the current thesis. For example, a highly significant difference would be evident between the severities of several subsequent injury groupings and their associated index injuries (e.g. recurrent match injuries) in Chapter 5 when assessed using *P*-values obtained from a paired *t*-test. However, this is primarily due to the large sample size (>1000 samples). In reality, these differences were not practically important, as evidenced by the small effects sizes. Secondly, the magnitude-based inference approach produces probabilities reflecting the likelihood that a given effect is beneficial, trivial or harmful, based on where the likely range of the true value (confidence interval) lies in relation to the smallest worthwhile effect. In this way, decisions can be made in a manner that is likely to better reflect the way decisions are made in sports settings; that is, a consideration of the cost-benefit ratio, taking into account factors such as the cost of implementing a treatment/strategy or the cost of making a wrong decision. For example, a team considering the installation of an artificial pitch at their home venue would require the probability that such surfaces have a harmful effect on injury risk to be extremely small, given the player welfare and financial considerations. Traditional null-hypothesis statistical approaches do not facilitate such real-world decisions as effectively, and instead often lead to the dichotomisation of decisions based on the (arbitrarily chosen) $P < 0.05$ value.

The magnitude-based inference approach is also open to criticisms (e.g. Welsh and Knight, 2014). Perhaps the most common criticism is that the approach requires researchers to make an arbitrary and subjective decision regarding the threshold for the smallest worthwhile effect, whereas null-hypothesis testing may be considered more scientific and objective. In reply, it can be argued that there are in fact default scales for assessing effect magnitude (Cohen, 1994), which are defined by the data, and in cases where these are not appropriate, the authors should be the ones best-placed to decide on the smallest worthwhile effect for the variable they have chosen to measure, and should be able to justify such a decision (Batterham and

Hopkins, 2006). What is more, by presenting the effect estimate and its associated confidence intervals, other researchers are free to re-assess the results with an altered smallest worthwhile effect value, and then decide for themselves if they agree with study's conclusions. Overall, magnitude-based inferences were the most appropriate approach for answering the research questions proposed in this thesis.

Another methodological approach adopted throughout this thesis was the use of multi-level (random effects) models. Multi-level models were used to varying degrees in Chapters 3, 4, 6, 7 and 8. The longitudinal data analysed throughout this thesis contained repeated measurements/observations collected from players, which also contain a hierarchical structure whereby the players are clustered within a natural group (teams). Traditional analysis strategies (e.g. linear regression analysis) make the assumption that observations are uncorrelated. However, repeated observations taken from an individual, and those that are clustered within a higher-level unit (i.e. a team), will almost always be more similar than observations taken from different individuals and teams, due to a common risk factor or injury mechanism to which the individuals are exposed (Cook, 2010). Analyses that treat different within-person and within-team injuries as being statistically independent of one another run the risk of generating misleading results (Ullah et al., 2012), especially when combined with a dichotomous approach to making inferences (i.e. null hypothesis testing). Specifically, standard errors are typically smaller (but less robust) when significant random effects are not accounted for in a model, as estimations are made across a single population that is assumed to be homogenous, rather than over a range of different populations (Borenstein et al., 2010). This, in turn, could lead to Type I errors (false discoveries of clear substantial effects, when the true effect is null).

The investigations undertaken in Chapter 7 provided evidence of significant within-player and within-team clustering of these data. As such, the frailty models (which include random effects) provided a substantially improved fit to the sport injury data when compared to the Cox PH model, which did not account for within-person correlations. Despite this, due to the large sample size afforded in Chapter 7, the general inferences made regarding the effects of the investigated risk factors on overall injury risk are unlikely to have differed between these models.

However, had non-random-effects models (Cox PH) been used in the subset analyses of specific injury types, where the number of injury events was substantially smaller, divergent conclusions may well have been reached. Advances in analytical approaches (e.g. general linear mixed models and frailty models) that have occurred alongside improvements in computer hardware and software now enable the multi-level structure of data to be appropriately accounted for in an increasingly accessible manner (Dickinson and Basu, 2005). These approaches have allowed robust inferences to be made from the longitudinal data analysed throughout this thesis and, wherever feasible, should be incorporated in future investigations to ensure researchers arrive at accurate conclusions when multi-level data is analysed.

9.5 Practical implications and potential impact

The overarching aim of this programme of work was to produce research that could potentially inform practice and lead to a reduction in injury burden within the sport. Outlining the practical implications resulting from this thesis, and methods by which this knowledge may be translated to practice, is therefore paramount to achieving this aim. The stakeholders best-placed to act upon the knowledge generated in this thesis are likely to be medical/rehabilitation and strength and conditioning staff, coaches, Directors of Rugby and overall policy makers within the sport. The impact resulting from the uptake of these practical messages can be monitored via the Professional Rugby Injury Surveillance Project, primarily by evaluating whether worthwhile reductions in injury burden are achieved.

Firstly, the negative association between injuries and team success reported in Chapter 4 may be a cogent point when attempting to communicate the importance of injury prevention to key stakeholders (e.g. coaches and Directors of Rugby). As Ekstrand (2013) stated:

“Coaches and administrative staff are seldom interested in medical statistics; their main interest is performance (results) and economy.”

The results from Chapter 4 should therefore provide clear motivation for these stakeholders to work together with medical and fitness staff to prevent injuries. The integration of sports science into applied sporting contexts remains a key challenge (Martindale and Nash, 2013), but all of the practical implications suggested below are likely to benefit from the dissemination of how injuries and team success are correlated in this elite rugby setting.

Secondly, the facets of the game that carry the highest injury risk were identified in Chapter 3, and may now be used to guide future preventative work. For instance, the introduction (or reconsideration) of warm-up protocols during the half-time interval may be beneficial in reducing the incidence rate of injuries during the third quarter of matches, which was most likely higher than the first quarter, and possibly higher than the second and final quarter of matches. Indeed, a study involving high school American footballers reported a significant reduction in third quarter muscle sprain and strain injuries in teams that were randomised to undertake a three minute

warm-up routine following the half-time break (Bixler and Jones, 1992). A re-warm-up at half-time was also shown to preserve muscle temperature and maintain sprint performance at the onset of the second half in a semi-professional football population (Mohr et al., 2004). A half-time re-warm-up, alongside heat maintenance, hormonal priming, and caffeine/carbohydrate consumption strategies, therefore warrant further investigation in elite Rugby Union populations, as an easily implementable approach that may elicit small but worthwhile reductions in injury risk and attenuation of reductions in physical and cognitive performance during the initial stages of the second half (Russell et al., 2014). This example demonstrates how the results of Chapter 3 may be used to accurately guide future preventative work.

The subsequent injury relationships outlined in Chapter 5 can be used to drive targeted secondary prevention efforts, such as reconsideration of treatment, rehabilitation and return-to-play protocols for ankle lateral ligament injuries (to avoid early re-injury to the ankle joint capsule), and injuries related to the neck region. For example, treatment, rehabilitation and return-to-play protocols for ankle lateral ligament injuries should ensure that full restoration of both neuromuscular function and mechanical stability is achieved before the player returns to full training and match-play, in order to address the increased risk of early re-injury of the ankle joint capsule. Dissemination of these findings to the clinical sports medicine field will stimulate the necessary changes to, and further research of, these 'higher risk' injury diagnoses.

The topic of load (match and training) management from a player welfare perspective is currently a prominent issue in elite Rugby Union, with recent calls for the season structure to be changed to allow players to have longer rest periods between seasons. The following quote from the chairman of the (professional) Rugby Players' Association, on the subject of match loads in elite Rugby Union, demonstrates the relevance of the work undertaken in this thesis (Jones, 2014):

"I would certainly say we are testing the limits on what is attainable. There has to come a breaking point, and I hope before we come to that breaking point we have a serious look at the length of time a player gets to rest each season."

The studies presented in Chapters 7 and 8 are the first to specifically address these issues in elite Rugby Union, and so support and augment this qualitative evidence by providing novel data that may be used to inform policy and consensus on this topic. Specifically, the current season structure and limit for the number of matches elite English players are permitted to play in a given season (32 matches) may need to be re-evaluated, given the observed association between previous season match loads and injury risk in the subsequent season. Additionally, the monitoring of shorter-term cumulative training loads appears to be important for controlling injury risk, and is a factor that can be manipulated readily by the coaching teams. Following confirmation of these findings in a larger sample of teams, knowledge of the most important training load measures will be translated to Premiership teams (through club visits conducted as part of the Professional Rugby Injury Surveillance Project) so that they may be incorporated into practice. Given that the novel 'previous injury load' variable was also identified as a risk factor for injury in Chapter 7, a simple spreadsheet will be made available to Premiership teams to enable them to calculate, monitor, and respond to each player's previous injury load value.

The study outlined in Chapter 6 has already been used to inform policy regarding the use of artificial playing surfaces in elite Rugby Union. The results of this chapter (i.e. overall acute injury risk was not increased on artificial turf compared with natural grass, whilst abrasions were more common but few resulted in any reported time-loss) and the associated stakeholder report was used to inform the decision to allow a further English Premiership team to install an artificial playing surface for the 2014/15 season. Specifically, the report was presented and discussed at a governing body meeting, and was subsequently used to guide policy decision regarding the current and future use of artificial playing surfaces in professional Rugby Union. Additionally, the findings of this chapter will be used to identify areas for future research on this topic (discussed below).

9.6 Future research

Many of the research questions proposed in this thesis were addressed for the first time in an elite Rugby Union population. As such, this section outlines potential future studies that may build upon and advance the knowledge gained from these initial investigations.

Firstly, continued surveillance of the influence that artificial playing surfaces have upon injury risk in this setting is necessary, in order to allow analyses of specific injury diagnoses and the long-term effects of playing elite Rugby Union on such surfaces. Given the growing interest in the use of artificial surfaces for training and match-play across all levels of Rugby Union, it is critical that further robust work is undertaken promptly, to ensure that players' welfare is not jeopardised by their introduction. Specifically, an inter-cohort comparison between teams playing on artificial turf as their home facility versus teams playing on natural grass as their home facility would further our understanding of the influence that artificial pitches have upon broader aspects of injury risk. Training exposure on artificial playing surfaces is now being recorded within the England Professional Rugby Injury Surveillance Project, which will help to elucidate their impact on this facet of the game in future seasons. Moreover, studies incorporating appropriate tools for recording overuse injuries in relation to artificial playing surfaces are necessary (Clarsen et al., 2013).

Another important topic for future work is likely to be the exploration of within- and between-team variability in injury reporting within the England Professional Injury Surveillance Project. In particular, an investigation of the influence that divergent injury definitions (e.g. missed match versus time-loss) have upon the variability in injury reporting in this setting would be of interest. Such investigations would enable the elucidation of whether the benefits associated with recording minor injuries (i.e. a more complete understanding of epidemiology in this setting) are negated by unacceptable reliability and validity issues.

Perhaps the biggest challenge for future work in this field will be the integration of the performance/fitness effects of training loads and match loads, alongside their impact on likelihood of injury, as both elements are central to the optimal prescription of loads. A 'systems model' approach (Calvert et al., 1976) that includes

a measure of the relationship between training loads and likelihood of injury, in addition to predicted physical performance, warrants investigation in this setting. Using this approach, a precise consideration of the cost-benefit ratio associated with prescribing a given training load could be facilitated. Ultimately, in an elite sport setting, an approach of risk minimisation rather than risk elimination will be adopted (Orchard and Best, 2002). As such, models that address both of these elements (injury risk and performance) are clearly necessary, and have a better chance of being translated into practice than models that address only one facet. Moreover, the highly individual nature of these relationships can be accounted for (Hayes and Quinn, 2009).

The first requirement in the development of such a model would be the identification of suitable performance tests that could be used to accurately monitor key aspects of elite Rugby Union performance (e.g. strength and high-intensity intermittent running ability). These tests would ideally be undertaken weekly, with methodological consistency and maximal effort from participants (Clarke and Skiba, 2013). Secondly, the investigation of appropriate methods for quantifying daily training loads related to the specific components of Rugby Union performance would be required. For instance, global positioning system data may now be used to provide metabolic power data to create power-based metrics founded upon the critical power model (Kempton et al., 2014). These data may provide a more accurate measure of the metabolic stress associated with conditioning activities (compared to session RPE alone), but require further validation in intermittent sports. In addition, alternative methods of quantifying volume during resistance exercise (e.g. volume load and time under tension) would need to be implemented in order to allow for a more sensitive measure of resistance exercise loads (McBride et al., 2009). Recent investigations have also revealed that some training modes (skills, wrestling, strongman and speed sessions) may require a combination of internal- and external-load measures to best quantify the training dose (Weaving et al., 2014).

Predictions of injury likelihood based upon the values of various risk factor variables may be incorporated into this ‘systems model’ approach using methods outlined in this thesis (i.e. generalised linear mixed modelling techniques and machine learning models). In addition to the important risk factors identified in this thesis (i.e.

previous season match loads, cumulative training loads and previous injury loads), a multi-disciplinary approach will be required to identify additional pertinent risk factors that would improve the predictive capacity of such a model. For instance, analyses including psychological predictors of injury risk are sorely lacking in the literature, but these variables are likely to mediate many of the relationships between risk factors and the incitement of injury. Including these variables alongside other important risk factors, and using a methodology and analysis strategy that takes into account the cyclic nature of changing risk factors (Meeuwise et al., 2007), should be a goal of this future work.

Finally, qualitative investigations may be used to complement and guide other forms of investigation in this area. For example, in a study of the nature of player burnout in professional Rugby Union, the following quote is insightful, and could be as useful in informing practice and impacting upon injury risk as other traditional forms of quantitative research (Cresswell and Eklund, 2006):

“Some players felt an obligation or pressure to meet requirements placed on them (e.g., travel, playing while injured, training load) regardless of the impact this may have had on their welfare. This perceived pressure to comply with demands came from the belief that an individual must meet all demands placed on them to be a professional rugby player.”

This quote highlights player welfare matters that may be best addressed through promoting open and honest communication processes within teams (Yukelson, 1997). Combining knowledge of this nature with the quantitative evidence generated in this thesis (i.e. evidence of the effects that high cumulative training loads and previous season match loads have upon injury risk, and the negative association between injuries and team success) is likely to maximise the chances that such research is translated into injury prevention practice (Finch, 2006).

9.7 Thesis conclusion

The aim of this thesis has been to understand injury risk in elite Rugby Union, a sport which is facing increasing scrutiny regarding the level of injury burden experienced by its participants. To achieve this aim, six novel research questions were addressed using longitudinal injury data collected as part of the England Professional Rugby Injury Surveillance Project.

These investigations have confirmed the importance of injury prevention efforts for all elite Rugby Union stakeholders, as well as the need to use appropriate analysis strategies to account for the dynamic and clustered nature of sport injury data. The association of reduced injury burden with team success has been demonstrated for the first time in elite Rugby Union. Injury diagnoses (relating to the neck, ankle and hip flexors/quadriceps) with a higher risk of early recurrence were identified, and so reconsideration of treatment, rehabilitation and return-to-play protocols for these injuries is encouraged. Ensuing analyses determined the influence of several intrinsic (previous injury, match and training loads) and extrinsic (playing surface) risk factors for injury, which may be used to inform policies on these pertinent issues. Specifically, re-evaluation of the current season structure and match load limits for players is recommended, alongside the need to monitor players' shorter-term cumulative training loads and previous injury loads. The continued and possibly expanded use of artificial playing surfaces for elite Rugby Union matches is endorsed, so long as further surveillance is undertaken to allow analyses of their wider impact on injury risk to be carried out. Predictive models were also developed to predict the occurrence and severity of injuries within elite Rugby Union. These models require further refinement, but nonetheless demonstrate potential as an approach for reducing injury burden in this population.

The results from this programme of work thus provide a further contribution to our understanding of injury risk in elite Rugby Union, and have important implications for future injury prevention policy and research.

REFERENCES

- Alsop, J. C., Morrison, L., Williams, S. M., Chalmers, D. J. & Simpson, J. C. (2005) Playing conditions, player preparation and rugby injury: A case-control study. *Journal of Science and Medicine in Sport*, 8, 171-180.
- Altman, D. G. & Bland, J. M. (1994) Statistics Notes: Diagnostic tests: Predictive values. *BMJ*, 309, 102.
- Andersen, P. K. & Gill, R. D. (1982) Cox's regression model for counting processes: A large sample study. *The Annals of Statistics*, 10, 1100-1120.
- Anderson, J. R., Michalski, R. S., Michalski, R. S., Carbonell, J. G. & Mitchell, T. M. (1986) *Machine learning: An artificial intelligence approach*. Massachusetts, USA: Morgan Kaufmann Publishers.
- Anderson, S. J. (2002) When to return to play after an ankle sprain. *The Physician and Sports Medicine*, 30, 39.
- Andersson, H., Ekblom, B. & Krstrup, P. (2008) Elite football on artificial turf versus natural grass: Movement patterns, technical standards, and player impressions. *Journal of Sports Sciences*, 26, 113-122.
- Aranganayagi, S. & Thangavel, K. (2007) Clustering categorical data using silhouette coefficient as a relocating measure. *Conference on Computational Intelligence and Multimedia Applications*. Sivakasi, India, IEEE.
- Arnason, A., Sigurdsson, S. B., Gudmundsson, A., Holme, I., Engebretsen, L. & Bahr, R. (2004a) Physical fitness, injuries, and team performance in soccer. *Medicine and Science in Sports and Exercise*, 36, 278-285.
- Arnason, A., Sigurdsson, S. B., Gudmundsson, A., Holme, I., Engebretsen, L. & Bahr, R. (2004b) Risk factors for injuries in football. *Am J Sports Med*, 32, 5S-16S.
- Aschengrau, A. & Seage, G. R. (2003) Overview of Epidemiologic Study Designs. *Essentials of Epidemiology for Public Health*. Boston, USA: Jones and Bartlett.
- Askling, C. M., Nilsson, J. & Thorstensson, A. (2010) A new hamstring test to complement the common clinical examination before return to sport after injury. *Knee Surgery, Sports Traumatology, Arthroscopy*, 18, 1798-1803.
- Bahadorreza, O., Zeleznikow, J., MacMahon, C. & Dwyer, D. (2013) Supporting athlete selection and strategic planning in track cycling omnium: A statistical and machine learning approach. *Information Sciences*, 233, 200-213.

References

- Bahr, R. & Holme, I. (2003) Risk factors for sports injuries - A methodological approach. *British Journal of Sports Medicine*, 37, 384-392.
- Bahr, R. & Krosshaug, T. (2005) Understanding injury mechanisms: A key component of preventing injuries in sport. *British Journal of Sports Medicine*, 39, 324-329.
- Basler, R., Garcia, M. A. & Gooding, K. S. (2001) Immediate steps for treating abrasions. *The Physician and Sports Medicine*, 29, 69.
- Bates, D., Maechler, M. & Dai, B. The lme4 package. 2008; Available from: <http://cran.r-project.org/web/packages/lme4/lme4.pdf> [Accessed 01 August 2014].
- Bathgate, A., Best, J. P., Craig, G. & Jamieson, M. (2002) A prospective study of injuries to elite Australian rugby union players. *British Journal of Sports Medicine*, 36, 265-269.
- Batterham, A. M. & Hopkins, W. G. (2006) Making meaningful inferences about magnitudes. *International Journal of Sports Physiology and Performance*, 1, 50-57.
- Beardmore, A. L., Handcock, P. J. & Rehrer, N. J. (2005) Return-to-play after injury: Practices in New Zealand rugby union. *Physical Therapy in Sport*, 6, 24-30.
- Bengtsson, H., Ekstrand, J. & Hagglund, M. (2013) Muscle injury rates in professional football increase with fixture congestion: An 11-year follow-up of the UEFA Champions League injury study. *British Journal of Sports Medicine*, 47, 743-747.
- Bensing, J. (1983) The use of the RFE-classification system in research into communication between general practitioner and patient. *10th WONCA Conference on Family Medicine*. Singapore.
- Benson, B. W., McIntosh, A. S., Maddocks, D., Herring, S. A., Raftery, M. & Dvorak, J. (2013) What are the most effective risk-reduction strategies in sport concussion? *British Journal of Sports Medicine*, 47, 321-6.
- Best, J. P., McIntosh, A. S. & Savage, T. N. (2005) Rugby World Cup 2003 injury surveillance project. *British Journal of Sports Medicine*, 39, 812-817.
- Biau, D. J., Jolles, B. M. & Porcher, R. (2010) P value and the theory of hypothesis testing an explanation for new researchers. *Clinical Orthopaedics and Related Research*, 468, 885-892.

References

- Bird, Y. N., Waller, A. E., Marshall, S. W., Alsop, J. C., Chalmers, D. J. & Gerrard, D. F. (1998) The New Zealand rugby injury and performance project: V. Epidemiology of a season of rugby injury. *British Journal of Sports Medicine*, 32, 319-325.
- Bixler, B. & Jones, R. L. (1992) High-school football injuries: Effects of a post-halftime warm-up and stretching routine. *Fam Pract Res J*, 12, 131-9.
- Bizzini, M., Hancock, D. & Impellizzeri, F. (2012) Suggestions from the field for return to sports participation following anterior cruciate ligament reconstruction: Soccer. *Journal of Orthopaedic & Sports Physical Therapy*, 42, 304-312.
- Bjørneboe, J., Bahr, R. & Andersen, T. E. (2010) Risk of injury on third-generation artificial turf in Norwegian professional football. *British Journal of Sports Medicine*, 44, 794-798.
- Bleakley, C., Tully, M. & O'Connor, S. (2011) Epidemiology of adolescent rugby injuries: A systematic review. *Journal of Athletic Training*, 46, 555-565.
- Blettner, M., Sauerbrei, W., Schlehofer, B., Scheuchenpflug, T. & Friedenreich, C. (1999) Traditional reviews, meta-analyses and pooled analyses in epidemiology. *International Journal of Epidemiology*, 28, 1-9.
- Bonita, R. (2006) *Basic epidemiology*. Geneva, Switzerland: World Health Organization.
- Borenstein, M., Hedges, L. V., Higgins, J. & Rothstein, H. R. (2010) A basic introduction to fixed-effect and random-effects models for meta-analysis. *Research Synthesis Methods*, 1, 97-111.
- Borresen, J. & Lambert, M. I. (2009) The quantification of training load, the training response and the effect on performance. *Sports Medicine*, 39, 779-795.
- Bourke, J. B. (2006) Rugby union should ban contested scrums. *BMJ*, 332, 1281.
- Box-Steffensmeier, J. M. & De Boef, S. (2006) Repeated events survival models: The conditional frailty model. *Statistics in Medicine*, 25, 3518-3533.
- Breiman, L. (2001a) Random forests. *Machine Learning*, 45, 5-32.
- Breiman, L. (2001b) Statistical modeling: The two cultures (with comments and a rejoinder by the author). *Statistical Science*, 16, 199-231.
- Brink, M. S. (2010) Balancing stress and recovery in sports. *Center for Sports, Exercise and Health*. University of Groningen.

References

- Brink, M. S., Visscher, C., Arends, S., Zwerver, J., Post, W. J. & Lemmink, K. A. (2010) Monitoring stress and recovery: New insights for the prevention of injuries and illnesses in elite youth soccer players. *British Journal of Sports Medicine*, 44, 809-815.
- Brooks, J. H. (2004) The epidemiology of injuries in professional rugby union. University of Leicester.
- Brooks, J. H., Fuller, C. W., Kemp, S. P. & Reddin, D. B. (2005a) Epidemiology of injuries in English professional rugby union: Part 1 match injuries. *British Journal of Sports Medicine*, 39, 757-66.
- Brooks, J. H., Fuller, C. W., Kemp, S. P. & Reddin, D. B. (2005b) Epidemiology of injuries in English professional rugby union: Part 2 training injuries. *British Journal of Sports Medicine*, 39, 767-75.
- Brooks, J. H., Fuller, C. W., Kemp, S. P. & Reddin, D. B. (2006) Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *Am J Sports Med*, 34, 1297-1306.
- Brooks, J. H., Fuller, C. W., Kemp, S. P. & Reddin, D. B. (2008) An assessment of training volume in professional rugby union and its impact on the incidence, severity, and nature of match and training injuries. *J Sports Sci*, 26, 863-73.
- Brooks, J. H. & Kemp, S. P. (2008) Recent trends in rugby union injuries. *Clin Sports Med*, 27, 51-73.
- Brooks, J. H. & Kemp, S. P. (2011) Injury-prevention priorities according to playing position in professional rugby union players. *British Journal of Sports Medicine*, 45, 765-75.
- Brooks, J. H. M. & Fuller, C. W. (2006) The influence of methodological issues on the results and conclusions from epidemiological studies of sports injuries - Illustrative examples. *Sports Medicine*, 36, 459-472.
- Brooks, J. H. M., Fuller, C. W., Kemp, S. P. T. & Reddin, D. B. (2005c) A prospective study of injuries and training amongst the England 2003 Rugby World Cup squad. *British Journal of Sports Medicine*, 39, 288-93.
- Brown, S. R. & Brughelli, M. (2014) Determining return-to-sport status with a multi-component assessment strategy: A case study in rugby. *Phys Ther Sport*, 211-215.
- Bruin, G., Kuipers, H., Keizer, H. A. & Vandervusse, G. J. (1994) Adaptation and overtraining in horses subjected to increasing training loads. *Journal of Applied Physiology*, 76, 1908-1913.

References

- Burillo, P., Gallardo, L., Felipe, J. L. & Gallardo, A. M. (2012) Artificial turf surfaces: Perception of safety, sporting feature, satisfaction and preference of football users. *European Journal of Sport Science*, 14, 1-11.
- Burnham, K. P. & Anderson, D. R. (2004) Multimodel inference understanding AIC and BIC in model selection. *Sociological Methods & Research*, 33, 261-304.
- Cahill, N., Lamb, K., Worsfold, P., Headey, R. & Murray, S. (2012) The movement characteristics of English Premiership rugby union players. *Journal of Sports Sciences*, 1-9.
- Calvert, T., Banister, E. W., Savage, M. V. & Bach, T. (1976) A systems model of the effects of training on physical performance. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 94-102.
- Cameron, A. C. & Trivedi, P. K. (2013) *Regression analysis of count data*. Cambridge, UK: Cambridge University Press.
- Cazzola, D., Preatoni, E., Stokes, K. A., England, M. E. & Trewartha, G. (2014) A modified prebind engagement process reduces biomechanical loading on front row players during scrummaging: A cross-sectional study of 11 elite teams. *British Journal of Sports Medicine*, bjsports-2013-092904.
- Chalmers, D. J. (2002) Injury prevention in sport: Not yet part of the game? *Injury Prevention*, 8, IV22-IV25.
- Chalmers, D. J., Samaranayaka, A., Gulliver, P. & McNoe, B. (2012) Risk factors for injury in rugby union football in New Zealand: A cohort study. *British Journal of Sports Medicine*, 46, 95-102.
- Checkoway, H. (1991) Data pooling in occupational studies. *Journal of Occupational and Environmental Medicine*, 33, 1257-1260.
- Clarke, D. C. & Skiba, P. F. (2013) Rationale and resources for teaching the mathematical modeling of athletic training and performance. *Advances in Physiology Education*, 37, 134-152.
- Clarke, N., Farthing, J. P., Norris, S. R., Arnold, B. E. & Lanovaz, J. L. (2013) Quantification of training load in Canadian Football: Application of Session-RPE in collision-based team sports. *The Journal of Strength & Conditioning Research*, 27, 2198-2205.
- Clarkson, P. M. & Tremblay, I. (1988) Exercise-induced muscle damage, repair, and adaptation in humans. *J Appl Physiol*, 65, 1-6.

References

- Clarsen, B., Myklebust, G. & Bahr, R. (2013) Development and validation of a new method for the registration of overuse injuries in sports injury epidemiology: The Oslo Sports Trauma Research Centre (OSTRC) Overuse Injury Questionnaire. *British Journal of Sports Medicine*, 47, 495-502.
- Cohen, J. (1994) The earth is round ($p < .05$). *American Psychologist*, 49, 997-1003.
- Colby, M., Dawson, B., Heasman, J., Rogalski, B. & Gabbett, T. J. (2014) Accelerometer and GPS-derived running loads and injury risk in elite Australian footballers. *The Journal of Strength & Conditioning Research*, Publish Ahead of Print, 10.1519/JSC.0000000000000362.
- Cook, I. (2010) Analysing recurrent events in exercise science and sports medicine. *South African Journal of Sports Medicine*, 22, 44-45.
- Cox, D. R. (1972) Regression models and life-tables. *Journal of the Royal Statistical Society Series B-Statistical Methodology*, 34, 187-220.
- Creighton, D. W., Shrier, I., Shultz, R., Meeuwisse, W. H. & Matheson, G. O. (2010) Return-to-play in sport: A decision-based model. *Clinical Journal of Sport Medicine*, 20, 379-385.
- Cresswell, S. & Eklund, R. (2006) The nature of player burnout in rugby: Key characteristics and attributions. *Journal of Applied Sport Psychology*, 18, 219-239.
- Cross, T. M., Gibbs, N., Houang, M. T. & Cameron, M. (2004) Acute quadriceps muscle strains: Magnetic resonance imaging features and prognosis. *Am J Sports Med*, 32, 710-9.
- Cunniffe, B., Hore, A. J., Whitcombe, D. M., Jones, K. P., Baker, J. S. & Davies, B. (2010) Time course of changes in immunoendocrine markers following an international rugby game. *European Journal of Applied Physiology*, 108, 113-122.
- Dauty, M. & Collon, S. (2011) Incidence of injuries in French professional soccer players. *International Journal of Sports Medicine*, 32, 965-969.
- Davidson, R. M. (1987) Schoolboy rugby injuries, 1969-1986. *Medical Journal of Australia*, 147, 119-120.
- Dayton, C. M. (2003) Model comparisons using information measures. *Journal of Modern Applied Statistical Methods*, 2, 281-292.
- Deeks, J. J. & Altman, D. G. (2004) Diagnostic tests 4: Likelihood ratios. *BMJ*, 329, 168-169.

References

- Dellal, A., Lago-Peñas, C., Rey, E., Chamari, K. & Orhant, E. (2013) The effects of a congested fixture period on physical performance, technical activity and injury rate during matches in a professional soccer team. *British Journal of Sports Medicine*, 1-5.
- Di Michele, R., Di Renzo, A. M., Ammazalorso, S. & Merni, F. (2009) Comparison of physiological responses to an incremental running test on treadmill, natural grass, and synthetic turf in young soccer players. *Journal of Strength and Conditioning Research*, 23, 939-945.
- Dickinson, L. M. & Basu, A. (2005) Multilevel modeling and practice-based research. *Ann Fam Med*, 3 Suppl 1, S52-60.
- Drakos, M. C., Taylor, S. A., Fabricant, P. D. & Haleem, A. M. (2013) Synthetic playing surfaces and athlete health. *Journal of the American Academy of Orthopaedic Surgeons*, 21, 293-302.
- Drawer, S. (2001) Risk evaluation in professional football. Loughborough University.
- Drawer, S. & Fuller, C. W. (2002) Evaluating the level of injury in English professional football using a risk based assessment process. *British Journal of Sports Medicine*, 36, 446-451.
- Dupont, G., Nedelec, M., McCall, A., McCormack, D., Berthoin, S. & Wisloff, U. (2010) Effect of 2 soccer matches in a week on physical performance and injury rate. *American Journal of Sports Medicine*, 38, 1752-1758.
- Duthie, G. M., Pyne, D. B., Hopkins, W. G., Livingstone, S. & Hooper, S. L. (2006) Anthropometry profiles of elite rugby players: Quantifying changes in lean mass. *British Journal of Sports Medicine*, 40, 202-207.
- Edelmann-Nusser, J., Hohmann, A. & Henneberg, B. (2002) Modeling and prediction of competitive performance in swimming upon neural networks. *European Journal of Sport Science*, 2, 1-10.
- van den Eijnde, W. A. J., Peppelman, M., Lamers, E. A. D., van de Kerkhof, P. C. M. & van Erp, P. E. J. (2014) Understanding the acute skin injury mechanism caused by player-surface contact during soccer: A survey and systematic review. *Orthopaedic Journal of Sports Medicine*, 2, 1-8.
- Eirale, C., Tol, J. L., Farooq, A., Smiley, F. & Chalabi, H. (2013) Low injury rate strongly correlates with team success in Qatari professional football. *British Journal of Sports Medicine*, 47, 807-8.
- Ekstrand, J. (2008) Epidemiology of football injuries. *Science & Sports*, 23, 73-77.

References

- Ekstrand, J. (2013) Keeping your top players on the pitch: The key to football medicine at a professional level. *British Journal of Sports Medicine*, 47, 723-724.
- Ekstrand, J., Hägglund, M. & Fuller, C. (2011) Comparison of injuries sustained on artificial turf and grass by male and female elite football players. *Scandinavian Journal of Medicine & Science in Sports*, 21, 824-832.
- Ekstrand, J. & Nigg, B. M. (1989) Surface-related injuries in soccer. *Sports Medicine*, 8, 56-62.
- Ekstrand, J., Timpka, T. & Hägglund, M. (2006) Risk of injury in elite football played on artificial turf versus natural grass: A prospective two-cohort study. *British Journal of Sports Medicine*, 40, 975-980.
- Ekstrand, J., Walden, M. & Hägglund, M. (2004a) A congested football calendar and the wellbeing of players: Correlation between match exposure of European footballers before the World Cup 2002 and their injuries and performances during that World Cup. *British Journal of Sports Medicine*, 38, 493-497.
- Ekstrand, J., Walden, M. & Hägglund, M. (2004b) Risk for injury when playing in a national football team. *Scandinavian Journal of Medicine & Science in Sports*, 14, 34-38.
- von Elm, E., Altman, D. G., Egger, M., Pocock, S. J., Gøtzsche, P. C., Vandenbroucke, J. P. & Strebe, I. (2007) The strengthening the reporting of observational studies in epidemiology (STROBE) statement: Guidelines for reporting observational studies. *Preventive Medicine*, 45, 247-251.
- Emery, C. A. (2007) Considering cluster analysis in sport medicine and injury prevention research. *Clin J Sport Med*, 17, 211-4.
- Eurorugby Club Ranking. European Club Rugby Ranking Table. 2013; Available from: <http://www.eurorugby.com/modules.php?name=Rdesc> [Accessed 12 June 2013].
- Feeley, B. T., Kennelly, S., Barnes, R. P., Muller, M. S., Kelly, B. T., Rodeo, S. A. & Warren, R. F. (2008) Epidemiology of National Football League training camp injuries from 1998 to 2007. *American Journal of Sports Medicine*, 36, 1597-1603.
- Finch, C. (2006) A new framework for research leading to sports injury prevention. *Journal of Science and Medicine in Sport*, 9, 3-9.
- Finch, C. F. & Cook, J. (2013) Categorising sports injuries in epidemiological studies: The subsequent injury categorisation (SIC) model to address multiple, recurrent and exacerbation of injuries. *British Journal of Sports Medicine*.

References

- Flom, P. L. & Cassell, D. L. (2007) Stopping stepwise: Why stepwise and similar selection methods are bad, and what you should use. *NorthEast SAS Users Group Inc 20th Annual Conference*. Baltimore, USA.
- Foster, C. (1998) Monitoring training in athletes with reference to overtraining syndrome. *Medicine and Science in Sports and Exercise*, 30, 1164-1168.
- Foster, C., Daines, E., Hector, L., Snyder, A. C. & Welsh, R. (1996) Athletic performance in relation to training load. *Wisconsin Medical Journal*, 95, 370-4.
- Foster, C., Florhaug, J. A., Franklin, J., Gottschall, L., Hrovatin, L. A., Parker, S., Doleshal, P. & Dodge, C. (2001) A new approach to monitoring exercise training. *The Journal of Strength & Conditioning Research*, 15, 109-115.
- Frick, R. W. (1996) The appropriate use of null hypothesis testing. *Psychological Methods*, 1, 379-390.
- Fuller, C. & Walker, J. (2006) Quantifying the functional rehabilitation of injured football players. *British Journal of Sports Medicine*, 40, 151-157.
- Fuller, C. W. (1995) Implications of health and safety legislation for the professional sportsman. *British Journal of Sports Medicine*, 29, 5-9.
- Fuller, C. W., Bahr, R., Dick, R. W. & Meeuwisse, W. H. (2007a) A framework for recording recurrences, reinjuries, and exacerbations in injury surveillance. *Clinical Journal of Sport Medicine*, 17, 197-200.
- Fuller, C. W., Brooks, J. H., Cancea, R. J., Hall, J. & Kemp, S. P. (2007b) Contact events in rugby union and their propensity to cause injury. *British Journal of Sports Medicine*, 41, 862-867.
- Fuller, C. W., Caswell, S. E. & Zimbwa, T. (2010a) Do mismatches between teams affect the risk of injury in the Rugby World Cup? *J Sci Med Sport*, 13, 36-8.
- Fuller, C. W., Clarke, L. & Molloy, M. G. (2010b) Risk of injury associated with rugby union played on artificial turf. *Journal of Sports Sciences*, 28, 563-570.
- Fuller, C. W., Laborde, F., Leather, R. J. & Molloy, M. G. (2008) International Rugby Board Rugby World Cup 2007 injury surveillance study. *British Journal of Sports Medicine*, 42, 452-459.
- Fuller, C. W., Molloy, M. G., Bagate, C., Bahr, R., Brooks, J. H. M., Donson, H., Kemp, S. P. T., McCrory, P., McIntosh, A. S., Meeuwisse, W. H., Quarrie, K. L., Raftery, M. & Wiley, P. (2007c) Consensus statement on injury definitions

References

- and data collection procedures for studies of injuries in rugby union. *British Journal of Sports Medicine*, 41, 328-331.
- Fuller, C. W., Raftery, M., Readhead, C., Targett, S. G. R. & Molloy, M. G. (2009) Impact of the International Rugby Board's experimental law variations on the incidence and nature of match injuries in southern hemisphere professional rugby union. *South African Medical Journal*, 99, 232-237.
- Fuller, C. W., Sheerin, K. & Targett, S. (2012a) Rugby World Cup 2011: International Rugby Board injury surveillance study. *British Journal of Sports Medicine*, 42, 452-459.
- Fuller, C. W., Taylor, A. E., Brooks, J. H. M. & Kemp, S. P. T. (2012b) Changes in the stature, body mass and age of English professional rugby players: A 10-year review. *Journal of Sports Sciences*, 1-8.
- Fuller, G. W., Kemp, S. P. T. & Decq, P. (2014) The International Rugby Board (IRB) Pitch Side Concussion Assessment trial: A pilot test accuracy study. *British Journal of Sports Medicine*.
- Fyfe, J. J., Opar, D. A., Williams, M. D. & Shield, A. J. (2013) The role of neuromuscular inhibition in hamstring strain injury recurrence. *J Electromyogr Kinesiol*, 23, 523-30.
- Gabbett, T., Minbashian, A. & Finch, C. (2007) Influence of environmental and ground conditions on injury risk in rugby league. *Journal of Science and Medicine in Sport*, 10, 211-218.
- Gabbett, T. J. (2004) Influence of training and match intensity on injuries in rugby league. *Journal of Sports Sciences*, 22, 409-417.
- Gabbett, T. J. (2005) Influence of playing position on the site, nature, and cause of rugby league injuries. *J Strength Cond Res*, 19, 749-55.
- Gabbett, T. J. (2006) A comparison of physiological and anthropometric characteristics among playing positions in sub-elite rugby league players. *Journal of Sports Sciences*, 24, 1273-1280.
- Gabbett, T. J. (2008) Influence of fatigue on tackling technique in rugby league players. *Journal of Strength and Conditioning Research*, 22, 625-632.
- Gabbett, T. J. (2010) The development and application of an injury prediction model for noncontact, soft-tissue injuries in elite collision sport athletes. *Journal of Strength and Conditioning Research*, 24, 2593-2603.

References

- Gabbett, T. J. & Domrow, N. (2007) Relationships between training load, injury, and fitness in sub-elite collision sport athletes. *Journal of Sports Sciences*, 25, 1507-1519.
- Gabbett, T. J. & Jenkins, D. G. (2011) Relationship between training load and injury in professional rugby league players. *Journal of Science and Medicine in Sport*, 14, 204-209.
- Gabbett, T. J. & Ullah, S. (2012) Relationship between running loads and soft-tissue injury in elite team sport athletes. *Journal of Strength & Conditioning Research* 26, 953-960.
- Gabbett, T. J., Ullah, S. & Finch, C. F. (2012a) Identifying risk factors for contact injury in professional rugby league players - Application of a frailty model for recurrent injury. *Journal of Science and Medicine in Sport*, 15, 496-504.
- Gabbett, T. J., Ullah, S., Jenkins, D. & Abernethy, B. (2012b) Skill qualities as risk factors for contact injury in professional rugby league players. *Journal of Sports Sciences*, 30, 1421-7.
- Gabriel, S. E. (2001) The epidemiology of rheumatoid arthritis. *Rheumatic Disease Clinics of North America*, 27, 269-281.
- Gains, G. L., Swedenhjelm, A. N., Mayhew, J. L., Bird, H. M. & Houser, J. J. (2010) Comparison of speed and agility performance of college football players on field turf and natural grass. *The Journal of Strength & Conditioning Research*, 24, 2613-2617.
- Gamble, P. (2004) Physical preparation for elite-level rugby union football. *Strength and Conditioning Journal*, 26, 10-23.
- Gardner, A., Iverson, G. L. & McCrory, P. (2014) Chronic traumatic encephalopathy in sport: A systematic review. *British Journal of Sports Medicine*, 48, 84-90.
- Garraway, M. & Macleod, D. (1995) Epidemiology of rugby football injuries. *Lancet*, 345, 1485-1487.
- Garraway, W. M., Lee, A. J., Hutton, S. J., Russell, E. & Macleod, D. A. D. (2000) Impact of professionalism on injuries in rugby union. *British Journal of Sports Medicine*, 34, 348-351.
- Garraway, W. M., Lee, A. J., Macleod, D. A. D., Telfer, J. W., Deary, I. J. & Murray, G. D. (1999) Factors influencing tackle injuries in rugby union football. *British Journal of Sports Medicine*, 33, 37-41.

References

- Gaulrapp, H., Siebert, C. & Rosemeyer, B. (1999) Injury and exertion patterns in football on artificial turf. *Sportverletz Sportschaden*, 13, 102-6.
- Geisser, S. (1993) *Predictive Inference*. Florida, USA: CRC Press.
- Gerrard, D. F. (1998) The use of padding in rugby union - An overview. *Sports Medicine*, 25, 329-332.
- Gerrard, D. F., Waller, A. E. & Bird, Y. N. (1994) The New-Zealand rugby injury and performance project. 2. Previous injury experience of a rugby-playing cohort. *British Journal of Sports Medicine*, 28, 229-233.
- Gianotti, S. M., Quarrie, K. L. & Hume, P. A. (2009) Evaluation of RugbySmart: A rugby union community injury prevention programme. *J Sci Med Sport*, 12, 371-375.
- Gill, N., Beaven, C. & Cook, C. (2006) Effectiveness of post-match recovery strategies in rugby players. *British Journal of Sports Medicine*, 40, 260-263.
- Gissane, C. (2003) The epidemiological approach to sports injury: The case for rugby league. *Department of Health and Social Care*. London, Brunel University.
- Gissane, C., White, J., Kerr, K. & Jennings, D. (2001) An operational model to investigate contact sports injuries. *Medicine and Science in Sports and Exercise*, 33, 1999-2003.
- Glynn, R. J. & Buring, J. E. (1996) Ways of measuring rates of recurrent events. *BMJ*, 312, 364-7.
- Gordon, J. E. (1949) The epidemiology of accidents. *American Journal of Public Health and the Nation's Health*, 39, 504-15.
- Guskiewicz, K. M., McCrea, M., Marshall, S. W., Cantu, R. C., Randolph, C., Barr, W., Onate, J. A. & Kelly, J. P. (2003) Cumulative effects associated with recurrent concussion in collegiate football players: The NCAA Concussion Study. *The Journal of the American Medical Association*, 290, 2549-2555.
- Haertung, J. (2011) Frailty models in survival analysis. *Department of Medical Epidemiology, Biostatistics, and Computer Science*, 38, 255-273.
- Hagel, B. & Meeuwisse, W. (2004) Risk compensation - A "side effect" of sport injury prevention? *Clinical Journal of Sport Medicine*, 14, 193-196.

References

- Hägglund, M., Walden, M. & Ekstrand, J. (2006) Previous injury as a risk factor for injury in elite football: A prospective study over two consecutive seasons. *British Journal of Sports Medicine*, 40, 767-772.
- Hägglund, M., Walden, M. & Ekstrand, J. (2007) Lower reinjury rate with a coach-controlled rehabilitation program in amateur male soccer: A randomized controlled trial. *Am J Sports Med*, 35, 1433-42.
- Hägglund, M., Walden, M. & Ekstrand, J. (2009a) UEFA injury study - An injury audit of European Championships 2006 to 2008. *British Journal of Sports Medicine*, 43, 483-489.
- Hägglund, M., Waldén, M. & Ekstrand, J. (2009b) Injuries among male and female elite football players. *Scandinavian Journal of Medicine & Science in Sports*, 19, 819-827.
- Hägglund, M., Walden, M., Magnusson, H., Kristenson, K., Bengtsson, H. & Ekstrand, J. (2013) Injuries affect team performance negatively in professional football: An 11-year follow-up of the UEFA Champions League injury study. *British Journal of Sports Medicine*, 47, 738-42.
- Hair, J. F., Black, W. C., Babin, B. J. & Anderson, R. E. (2009) *Multivariate data analysis - A global perspective*. New Jersey, USA: Pearson.
- Hamilton, G. M., Meeuwisse, W. H., Emery, C. A. & Shrier, I. (2011a) Subsequent injury definition, classification, and consequence. *Clinical Journal of Sport Medicine*, 21, 508-514.
- Hamilton, G. M., Meeuwisse, W. H., Emery, C. A., Steele, R. J. & Shrier, I. (2011b) Past injury as a risk factor: An illustrative example where appearances are deceiving. *American Journal of Epidemiology*, 173, 941-948.
- Hardin, E. C., van den Bogert, A. J. & Hamill, J. (2004) Kinematic adaptations during running: Effects of footwear, surface, and duration. *Medicine and Science in Sports and Exercise*, 36, 838-844.
- Hardin, J. W., Hilbe, J. M. & Hilbe, J. (2007) *Generalized linear models and extensions*. Texas, USA: Stata Press.
- Hawkins, R. D. & Fuller, C. W. (1999) A prospective epidemiological study of injuries in four English professional football clubs. *British Journal of Sports Medicine*, 33, 196-203.
- Hayen, A. (2006) Clustered data in sports research. *Journal of Science and Medicine in Sport*, 9, 165-168.

References

- Hayes, P. & Quinn, M. (2009) A mathematical model for quantifying training. *European Journal of Applied Physiology*, 106, 839-847.
- Health and Safety Executive (1995) *Generic terms and concepts in the assessment and regulation of industrial risks*. Sudbury, United Kingdom: HSE Books.
- Heiser, T. M., Weber, J., Sullivan, G., Clare, P. & Jacobs, R. R. (1984) Prophylaxis and management of hamstring muscle injuries in intercollegiate football players. *Am J Sports Med*, 12, 368-70.
- Helmy, A., Agarwal, M. & Hutchinson, P. J. (2013) *Concussion and sport*.
- Hertel, J. (2000) Functional instability following lateral ankle sprain. *Sports Medicine*, 29, 361-371.
- Higham, D. G., Hopkins, W. G., Pyne, D. B. & Anson, J. M. (2014) Performance indicators related to points scoring and winning in international rugby sevens. *Journal of Sports Science & Medicine*, 13, 358-364.
- Hlobil, H., van Mechelen, W. & Kemper, H. C. G. (1987) *How can sports injuries be prevented?* The Netherlands: National Institute for Sports Health Care.
- Hoffman, J. R. & Kang, J. (2003) Strength changes during an in-season resistance-training program for football. *The Journal of Strength & Conditioning Research*, 17, 109-114.
- Holt, C. C. (2004) Forecasting seasonals and trends by exponentially weighted moving averages. *International Journal of Forecasting*, 20, 5-10.
- Holtzhausen, L. J., Schwellnus, M. P., Jakoet, I. & Pretorius, A. L. (2006) The incidence and nature of injuries in South African rugby players in the rugby Super 12 competition. *South African Medical Journal*, 96, 1260-1265.
- Hopkins, W., Marshall, S., Batterham, A. & Hanin, J. (2009a) Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, 41, 3-12.
- Hopkins, W. G. Analysis of validity by linear regression (Excel spreadsheet). 2000; Available from: <http://sportsci.org/resource/stats/xvalid.xls> [Accessed 26 June 2014].
- Hopkins, W. G. A Scale of Magnitudes for Effect Statistics 2002; Available from: <http://www.sportsci.org/resource/stats/effectmag.html> [Accessed 26 June 2014].

References

- Hopkins, W. G. (2006a) Estimating sample size for magnitude-based inferences. *Sportscience*, 10, 63-70.
- Hopkins, W. G. (2006b) A spreadsheet for combining outcomes from several subject groups. *Sportscience*, 10, 51-53.
- Hopkins, W. G. (2007) A spreadsheet for deriving a confidence interval, mechanistic inference and clinical inference from a p value. *Sportscience*, 11, 16-20.
- Hopkins, W. G. (2010) Linear models and effect magnitudes for research, clinical and practical applications. *Sportscience*, 14, 49-57.
- Hopkins, W. G. Precision of measurement. 2011; Available from: www.newstats.org/precision.html [Accessed 18 August 2013].
- Hopkins, W. G., Hawley, J. A. & Burke, L. M. (1999) Design and analysis of research on sport performance enhancement. *Medicine and Science in Sports and Exercise*, 31, 472-485.
- Hopkins, W. G., Marshall, S. W., Batterham, A. M. & Hanin, J. (2009b) Progressive statistics for studies in Sports Medicine and Exercise Science. *Medicine and Science in Sports and Exercise*, 41, 3-12.
- Hopkins, W. G., Marshall, S. W., Quarrie, K. L. & Hume, P. A. (2007) Risk factors and risk statistics for sports injuries. *Clinical Journal of Sport Medicine*, 17, 208-210.
- Hoskins, W., Pollard, H., Daff, C., Odell, A., Garbutt, P., McHardy, A., Hardy, K. & Dragasevic, G. (2009) Low back pain status in elite and semi-elite Australian football codes: A cross-sectional survey of football (soccer), Australian rules, rugby league, rugby union and non-athletic controls. *BMC Musculoskeletal Disorders*, 10, 1-9.
- Hougaard, P. (1991) Modeling heterogeneity in survival-data. *Journal of Applied Probability*, 28, 695-701.
- Hougaard, P. (1995) Frailty models for survival data. *Lifetime Data Analysis*, 1, 255-273.
- Hughes, D. C. & Fricker, P. A. (1994) A prospective survey of injuries to first-grade rugby union players. *Clinical Journal of Sport Medicine*, 4, 249-256.
- Hulin, B. T., Gabbett, T. J., Blanch, P., Chapman, P., Bailey, D. & Orchard, J. W. (2014) Spikes in acute workload are associated with increased injury risk in elite cricket fast bowlers. *Br J Sports Med*, 48, 708-12.

References

- Hunter, W. G. & Hunter, J. S. (1978) *Statistics for experimenters*. New York, USA: Wiley.
- International Rugby Board. Regulation 22: Standard relating to the use of artificial playing surfaces. 2008; Available from: http://www.irb.com/mm/document/lawsregs/0/regulation22080611_6080.pdf [Accessed 15 January 2014].
- International Rugby Board. IRB Policy on Hygiene, Infection Control and Prevention of Infection. 2010; Available from: <http://www.irbplayerwelfare.com/?documentid=23> [Accessed 16 September 2014].
- International Rugby Board. Men's Next Senior National Representative Team. 2012; Available from: <http://www.irb.com/mm/Document/LawsRegs/Regulations/02/06/29/68/nsrt.pdf> [Accessed 10 October 2012].
- International Rugby Board. IRB to change name to World Rugby. 2014; Available from: <http://www.irb.com/newsmedia/mediazone/pressrelease/newsid=2072837.html#irb+change+name+world+rugby> [Accessed 28 August 2014].
- Ivarsson, A., Johnson, U. & Podlog, L. (2013) Psychological predictors of injury occurrence: A prospective investigation of professional Swedish soccer players. *Journal of Sport Rehabilitation*, 22, 19-26.
- Jakoet, I. & Noakes, T. D. (1998) A high rate of injury during the 1995 Rugby World Cup. *South African Medical Journal*, 88, 45-47.
- The Telegraph (2014a) 'Give us a longer break', pleads England hooker Dylan Hartley as new season and World Cup loom. James, S.
- The Telegraph (2014b) James Simpson-Daniel's retirement highlights fact that rugby's finest need more rest and less play. James, S.
- Jones, C. Rugby Players' Association: Season structure must change. 2014; Available from: <http://www.bbc.co.uk/sport/0/rugby-union/29796327> [Accessed 28 October 2014].
- Jones, P. L., Kerwin, D. G., Irwin, G. & Nokes, L. D. M. (2009) Three dimensional analysis of knee biomechanics when landing on natural turf and football turf. *Journal of Medical and Biological Engineering*, 29, 184-188.
- Jones, S. J., Lyons, R. A., Evans, R., Newcombe, R. G., Nash, P., McCabe, M. & Palmer, S. R. (2004) Effectiveness of rugby headgear in preventing soft tissue

References

- injuries to the head: A case-control and video cohort study. *British Journal of Sports Medicine*, 38, 159-162.
- Joseph, A., Fenton, N. E. & Neil, M. (2006) Predicting football results using Bayesian nets and other machine learning techniques. *Knowledge-Based Systems*, 19, 544-553.
- Kahanov, L., Dusa, M. J., Wilkinson, S. & Roberts, J. (2005) Self-reported headgear use and concussions among collegiate men's rugby union players. *Research in Sports Medicine*, 13, 77-89.
- Kaiser, H. F. (1974) An index of factorial simplicity. *Psychometrika*, 39, 31-36.
- Kampakis, S. (2013) Comparison of machine learning methods for predicting the recovery time of professional football players after an undiagnosed injury. *Machine Learning and Data Mining for Sports Analytics*. Prague, Czech Republic.
- Kanaras, V., Metaxas, T. I., Mandroukas, A., Gissis, I., Zafeiridis, A., Riganas, C. S., Manolopoulos, E. & Vrabas, I. S. (2014) The effect of natural and artificial grass on sprinting performance in young soccer players. *American Journal of Sports Science*, 2, 1-4.
- Kaplan, E. L. & Meier, P. (1958) Nonparametric-estimation from incomplete observations. *Journal of the American Statistical Association*, 53, 457-481.
- Kara, S. D. (2013) Injuries in professional rugby union: A study of five year of injury data with training loads and travel as co-variates. Auckland University of Technology, Auckland, New Zealand.
- Kemp, S. P. T., Brooks, J. H. M., Cross, M., Fuller, C. W., T., A., Johnston, N., Smith, A., Taylor, A., Trewartha, G., Stokes, K. & Williams, S. England Professional Rugby Injury Surveillance Project 2012-2013 Season Report. 2013; Available from: http://www.rfu.com/news/2014/february/news-articles/~media/files/2014/takingpart/injury_audit_report_2014_.ashx [Accessed 05 June 2014].
- Kemp, S. P. T., Brooks, J. H. M., Fuller, C. W., Lidlow, K., Smith, A. & Taylor, A. (2011) England Rugby Premiership Injury and Training Audit: 2010-2011 Season Report.
- Kemp, S. P. T., Hudson, Z., Brooks, J. H. M. & Fuller, C. W. (2008) The epidemiology of head injuries in English professional rugby union. *Clinical Journal of Sport Medicine*, 18, 227-234.
- Kempton, T., Sirotic, A. C., Rampinini, E. & Coutts, A. J. (2014) Metabolic power demands of Rugby League match-play. *Int J Sports Physiol Perform*.

References

- Kerdok, A. E., Biewener, A. A., McMahon, T. A., Weyand, P. G. & Herr, H. M. (2002) Energetics and mechanics of human running on surfaces of different stiffnesses. *Journal of Applied Physiology*, 92, 469-478.
- Kerr, Z. Y., Marshall, S. W., Harding, H. P. & Guskiewicz, K. M. (2012) Nine-year risk of depression diagnosis increases with increasing self-reported concussions in retired professional football players. *The American Journal of Sports Medicine*, 40, 2206-2212.
- Killen, N. M., Gabbett, T. J. & Jenkins, D. G. (2010) Training loads and incidence of injury during the preseason in professional rugby league players. *Journal of Strength and Conditioning Research*, 24, 2079-2084.
- Kinchington, M. A., Ball, K. A. & Naughton, G. (2011) Effects of footwear on comfort and injury in professional rugby league. *Journal of Sports Sciences*, 29, 1407-1415.
- Kirby, R. L., Simms, F. C., Symington, V. J. & Garner, J. B. (1981) Flexibility and musculoskeletal symptomatology in female gymnasts and age-matched controls. *American Journal of Sports Medicine*, 9, 160-164.
- Kirkwood, B. R. & Sterne, J. A. C. (2003) *Essential medical statistics*. Oxford, UK: Blackwell Science.
- The Guardian (2014) Concerns grow as toll of rugby's culling fields proves a hit too many. Kitson, R. 13 May 2014.
- Kleinbaum, D. G. & Klein, M. (1996) *Survival analysis*. New York, USA: Springer.
- Klügl, M., Shrier, I., McBain, K., Shultz, R., Meeuwisse, W. H., Garza, D. & Matheson, G. O. (2010) The prevention of sport injury: An analysis of 12 000 published manuscripts. *Clinical Journal of Sport Medicine*, 20, 407-412.
- Knapik, J., Marshall, S., Lee, R., Darakjy, S., Jones, S., Mitchener, T., dela Cruz, G. & Jones, B. (2007) Mouthguards in sport activities history, physical properties and injury prevention effectiveness. *Sports Medicine*, 37, 117-144.
- Knapik, J. J., Sharp, M. A., Canham-Chervak, M., Hauret, K., Patton, J. F. & Jones, B. H. (2001) Risk factors for training-related injuries among men and women in basic combat training. *Medicine and Science in Sports and Exercise*, 33, 946-954.
- Kristenson, K., Bjørneboe, J., Waldén, M., Andersen, T. E., Ekstrand, J. & Häggglund, M. (2013) The Nordic Football Injury Audit: Higher injury rates for professional football clubs with third-generation artificial turf at their home venue. *British Journal of Sports Medicine*, 47, 775-781.

References

- Kuhn, M. & Johnson, K. (2013) *Applied Predictive Modeling*. New York, USA: Springer.
- Kumar, S. (1990) Cumulative load as a risk factor for low-back pain. *Spine* 15, 1311-1316.
- Kumar, S. (1994) A conceptual model of overexertion [correction of overexertion], safety, and risk of injury in occupational settings. *Hum Factors*, 36, 197-209.
- Kumar, S. (2001) Theories of musculoskeletal injury causation. *Ergonomics*, 44, 17-47.
- Kumar, S. & Narayan, Y. (1998) Spectral parameters of trunk muscles during fatiguing isometric axial rotation in neutral posture. *Journal of Electromyography and Kinesiology*, 8, 257-267.
- Kuss, O. (2002) How to use SAS for logistic regression with correlated data. *Proceedings of the 27th Annual SAS Users Group International Conference*.
- Latouche, A., Porcher, R. & Chevret, S. (2004) Sample size formula for proportional hazards modelling of competing risks. *Statistics in Medicine*, 23, 3263-74.
- Lavallee, L. & Flint, F. (1996) The relationship of stress, competitive anxiety, mood state, and social support to athletic injury. *J Athl Train*, 31, 296-9.
- Lee, A., Garraway, W., Hepburn, W. & Laidlaw, R. (2001a) Influence of rugby injuries on players' subsequent health and lifestyle: Beginning a long term follow up. *British Journal of Sports Medicine*, 35, 38-42.
- Lee, A. J., Garraway, W. M. & Arneil, D. W. (2001b) Influence of preseason training, fitness, and existing injury on subsequent rugby injury. *British Journal of Sports Medicine*, 35, 412-417.
- Liang, K.-Y. & Zeger, S. L. (1993) Regression analysis for correlated data. *Annual Review of Public Health*, 14, 43-68.
- Lindenfeld, T. N., Schmitt, D. J., Hendy, M. P., Mangine, R. E. & Noyes, F. R. (1994) Incidence of injury in indoor soccer. *The American Journal of Sports Medicine*, 22, 364-371.
- Littell, R., Henry, P. & Ammerman, C. (1998) Statistical analysis of repeated measures data using SAS procedures. *Journal of Animal Science*, 76, 1216-1231.
- Lorentzon, R., Wedren, H., Pietila, T. & Gustavsson, B. (1988) Injuries in international ice hockey - A prospective, comparative-study of injury incidence

References

- and injury types in international and swedish elite ice hockey. *American Journal of Sports Medicine*, 16, 389-391.
- Lower, T. (1995) Injury data collection in the rugby codes. *Australian Journal of Science and Medicine in Sport*, 27, 38-42.
- Lystad, R. P., Pollard, H. & Graham, P. L. (2009) Epidemiology of injuries in competition taekwondo: A meta-analysis of observational studies. *Journal of Science and Medicine in Sport*, 12, 614-621.
- MacQueen, A. E. & Dexter, W. W. (2010) Injury trends and prevention in rugby union football. *Current Sports Medicine Reports*, 9, 139-143.
- Madsen, D. (1983) *Successful Dissertations and Theses: A Guide to Graduate Student Research from Proposal to Completion*. San Francisco, USA: Jossey-Bass.
- Mahmood, A., Ullah, S. & Finch, C. (2014) Application of survival models in sports injury prevention research: A systematic review. *British Journal of Sports Medicine*, 48, 630.
- Malcolm, D., Sheard, K. & White, A. (2001) The management of injuries in elite rugby union: The effects of commercialization and globalization. *First World Congress of Sociology of Sport*. Seoul, South Korea.
- Mann, C. J. (2003) Observational research methods. Research design II: Cohort, cross sectional, and case-control studies. *Emergency Medicine Journal*, 20, 54-60.
- Martindale, R. & Nash, C. (2013) Sport science relevance and application: Perceptions of UK coaches. *Journal of Sports Sciences*, 31, 807-819.
- Maynard, I. W. & Howe, B. L. (1987) Interrelations of trait and state anxiety with game performance of rugby players. *Perceptual and Motor Skills*, 64, 599-602.
- McBride, J. M., McCaulley, G. O., Cormie, P., Nuzzo, J. L., Cavill, M. J. & Triplett, N. T. (2009) Comparison of methods to quantify volume during resistance exercise. *J Strength Cond Res*, 23, 106-10.
- McCrory, P. (2001) Do mouthguards prevent concussion? *British Journal of Sports Medicine*, 35, 81-82.
- McCrory, P., Davis, G. & Makdissi, M. (2012) Second impact syndrome or cerebral swelling after sporting head injury. *Current Sports Medicine Reports*, 11, 21-23.

References

- McCrory, P., Meeuwisse, W. H., Aubry, M., Cantu, B., Dvořák, J., Echemendia, R. J., Engebretsen, L., Johnston, K., Kutcher, J. S. & Raftery, M. (2013) Consensus statement on concussion in sport: The 4th International Conference on Concussion in Sport held in Zurich, November 2012. *British Journal of Sports Medicine*, 47, 250-258.
- McGrath, R. P., Whitehead, J. R. & Caine, D. J. (2014) The effects proprioceptive neuromuscular facilitation stretching on post-exercise delayed onset muscle soreness in young adults. *International Journal of Exercise Science*, 7, 14-21.
- McHugh, M., Connolly, D. J., Eston, R. & Gleim, G. (1999) Exercise-induced muscle damage and potential mechanisms for the repeated bout effect. *Sports Medicine*, 27, 157-170.
- McIntosh, A., Caponecchia, C. & Usman, J. (2011) Tackling risk compensation – A psycho-physical approach to measuring behaviour change. *British Journal of Sports Medicine*, 45, 362.
- McIntosh, A. S. (2005) Risk compensation, motivation, injuries, and biomechanics in competitive sport. *British Journal of Sports Medicine*, 39, 2-3.
- McIntosh, A. S. & McCrory, P. (2000) Impact energy attenuation performance of football headgear. *British Journal of Sports Medicine*, 34, 337-341.
- McIntosh, A. S. & McCrory, P. (2001) Effectiveness of headgear in a pilot study of under 15 rugby union football. *British Journal of Sports Medicine*, 35, 167-169.
- McIntosh, A. S., Savage, T. N., McCrory, P., Fréchède, B. O. & Wolfe, R. (2010) Tackle characteristics and injury in a cross section of rugby union football. *Medicine and Science in Sports and Exercise*, 42, 977-984.
- McLean, S. G., Felin, R. E., Suedekum, N., Calabrese, G., Passerallo, A. & Joy, S. (2007) Impact of fatigue on gender-based high-risk landing strategies. *Medicine and Science in Sports and Exercise*, 39, 502.
- McManus, A. (2000) Validation of an instrument for injury data collection in rugby union. *British Journal of Sports Medicine*, 34, 342-347.
- van Mechelen, W., Hlobil, H. & Kemper, H. C. G. (1992) Incidence, severity, etiology and prevention of sports injuries - A review of concepts. *Sports Medicine*, 14, 82-99.
- Meeuwisse, W. H., Tyreman, H., Hagel, B. & Emery, C. (2007) A dynamic model of etiology in sport injury: The recursive nature of risk and causation. *Clinical Journal of Sport Medicine* 17, 215-219.

References

- Meeuwisse, W. H. & Wiley, J. P. (2007) The Sport Medicine Diagnostic Coding System. *Clinical Journal of Sport Medicine*, 17, 205-207.
- Meir, R. (1993) Seasonal changes in estimates of body composition in professional rugby league players. *Sport Health*, 11, 27-31.
- Meir, R. A., McDonald, K. N. & Russell, R. (1997) Injury consequences from participation in professional rugby league: A preliminary investigation. *British Journal of Sports Medicine*, 31, 132-134.
- Mendiguchia, J. & Brughelli, M. (2011) A return-to-sport algorithm for acute hamstring injuries. *Physical Therapy in Sport*, 12, 2-14.
- Meyers, M. C. & Barnhill, B. S. (2004) Incidence, causes, and severity of high school football injuries on FieldTurf versus natural grass - A 5-year prospective study. *American Journal of Sports Medicine*, 32, 1626-1638.
- Milanez, V. F., Ramos, S. P., Okuno, N. M., Boullosa, D. A. & Nakamura, F. Y. (2013) Evidence of a non-linear dose-response relationship between training load and stress markers in elite female futsal players. *Journal of Sports Science and Medicine*, 12, 22-29.
- Mohammadi, F. (2007) Comparison of 3 preventive methods to reduce the recurrence of ankle inversion sprains in male soccer players. *The American Journal of Sports Medicine*, 35, 922-926.
- Mohr, M., Krstrup, P., Nybo, L., Nielsen, J. J. & Bangsbo, J. (2004) Muscle temperature and sprint performance during soccer matches – Beneficial effect of re-warm-up at half-time. *Scandinavian Journal of Medicine & Science in Sports*, 14, 156-162.
- Montgomery, P. G. & Hopkins, W. G. (2012) The effects of game and training loads on perceptual responses of muscle soreness in Australian Football. *International Journal of Sports Physiology and Performance*, 8, 312-318.
- Mortimer, J., Van Duijn, C., Chandra, V., Fratiglioni, L., Graves, A., Heyman, A., Jorm, A., Kokmen, E., Kondo, K. & Rocca, W. (1991) Head trauma as a risk factor for Alzheimer's disease: A collaborative re-analysis of case-control studies. *International Journal of Epidemiology*, 20, S28-S35.
- Neter, J., Wasserman, W. & Kutner, M. H. (1989) *Applied Linear Regression Models*. Chicago, USA: Irwin.
- Nordstrom, A., Nordstrom, P. & Ekstrand, J. (2014) Sports-related concussion increases the risk of subsequent injury by about 50% in elite male football players. *British Journal of Sports Medicine*, 48, 1447-1450.

References

- Norton, K., Schwerdt, S. & Lange, K. (2001) Evidence for the aetiology of injuries in Australian football. *British Journal of Sports Medicine*, 35, 418-423.
- Norton, K. I., Craig, N. & Olds, T. (1999) Evolution of Australian football: The impact on injury potential. *Journal of Science and Medicine in Sport*, 2, 8.
- Ofoghi, B., Zeleznikow, J., MacMahon, C. & Dwyer, D. (2013) Supporting athlete selection and strategic planning in track cycling omnium: A statistical and machine learning approach. *Information Sciences*, 233, 200-213.
- Olmos, M., Antelo, M., Vazquez, H., Smecuol, E., Maurino, E. & Bai, J. C. (2008) Systematic review and meta-analysis of observational studies on the prevalence of fractures in coeliac disease. *Digestive and Liver Disease*, 40, 46-53.
- Olsen, O., Myklebust, G., Engebretsen, L., Holme, I. & Bahr, R. (2003) Relationship between floor type and risk of ACL injury in team handball. *Scandinavian Journal of Medicine & Science in Sports*, 13, 299-304.
- Orchard, J. (1995) Orchard Sports Injury Classification System (OSICS). *Sports Health*, 11, 39-41.
- Orchard, J. & Best, T. M. (2002) The management of muscle strain injuries: An early return versus the risk of recurrence. *Clinical Journal of Sport Medicine*, 12, 3-5.
- Orchard, J., Best, T. M. & Verrall, G. M. (2005) Return to play following muscle strains. *Clinical Journal of Sport Medicine*, 15, 436-441.
- Orchard, J., Hoskins, W. & Chiro, M. (2007) For debate: Consensus injury definitions in team sports should focus on missed playing time. *Clinical Journal of Sport Medicine*, 17, 192-196.
- Orchard, J. & Seward, H. (2002) Epidemiology of injuries in the Australian Football League, seasons 1997-2000. *British Journal of Sports Medicine*, 36, 39-44.
- Orchard, J. W. (2001) Intrinsic and extrinsic risk factors for muscle strains in Australian football. *Am J Sports Med*, 29, 300-3.
- Orchard, J. W. (2009) On the value of team medical staff: Can the “Moneyball” approach be applied to injuries in professional football? *British Journal of Sports Medicine*, 43, 963-965.
- Orchard, J. W., James, T., Portus, M., Kountouris, A. & Dennis, R. (2009) Fast bowlers in cricket demonstrate up to 3- to 4-week delay between high workloads and increased risk of injury. *Am J Sports Med*, 37, 1186-92.

References

- Orchard, J. W., Walden, M., Hagglund, M., Orchard, J. J., Chivers, I., Seward, H. & Ekstrand, J. (2013) Comparison of injury incidences between football teams playing in different climatic regions. *Open Access J Sports Med*, 4, 251-60.
- Pain, M. T. G., Tsui, F. & Cove, S. (2008) In vivo determination of the effect of shoulder pads on tackling forces in rugby. *Journal of Sports Sciences*, 26, 855-862.
- Palmer-Green, D. S., Stokes, K. A., Fuller, C. W., England, M., Kemp, S. P. & Trewartha, G. (2013) Match injuries in English youth academy and schools rugby union - An epidemiological study. *The American Journal of Sports Medicine*, 41, 749-755.
- Peppelman, M., van den Eijnde, W. A. J., Langewouters, A. M. G., Weghuis, M. O. & van Erp, P. E. J. (2013) The potential of the skin as a readout system to test artificial turf systems: Clinical and immunohistological effects of a sliding on natural grass and artificial turf. *Int J Sports Med*, 34, 783-788.
- Perneger, T. V. (1998) What's wrong with Bonferroni adjustments. *BMJ*, 316, 1236-1238.
- Daily Mail (2014) Rugby's obsession with size and power is forcing the game to the brink of crisis. Peters, S. March 1 2014.
- Petrass, L. A. & Twomey, D. M. (2013) The relationship between ground conditions and injury: What level of evidence do we have? *Journal of Science and Medicine in Sport*, 16, 105-112.
- Piggott, B. (2008) The relationship between training load and incidence of injury and illness over a pre-season at an Australian Football League Club. *Computing, Health and Science*. Edith Cowan University.
- Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D. & R Core Team. nlme: Linear and Nonlinear Mixed Effects Models. 2014; Available from: <http://CRAN.R-project.org/package=nlme> [Accessed 21 Feb 2014].
- Poulos, C. C., Gallucci, J., Gage, W. H., Baker, J., Buitrago, S. & Macpherson, A. K. (2014) The perceptions of professional soccer players on the risk of injury from competition and training on natural grass and 3rd generation artificial turf. *BMC Sports Science, Medicine and Rehabilitation*, 6, 11-18.
- Powell, J. W. (1988) National high school athletic injury registry. *Am J Sports Med*, 16 Suppl 1, S134-5.
- Prentice, R. L., Williams, B. J. & Peterson, A. V. (1981) On the regression-analysis of multivariate failure time data. *Biometrika*, 68, 373-379.

References

- Putlur, P., Foster, C., Miskowski, J. A., Kane, M. K., Burton, S. E., Scheett, T. P. & McGuigan, M. R. (2004) Alteration of immune function in women collegiate soccer players and college students. *Journal of Sports Science and Medicine*, 3, 234-243.
- Quarrie, K. L. (2001) The New Zealand rugby injury and performance project. VI. A prospective cohort study of risk factors for injury in rugby union football. *British Journal of Sports Medicine*, 35, 157-166.
- Quarrie, K. L., Cantu, R. C. & Chalmers, D. J. (2002) Rugby union injuries to the cervical spine and spinal cord. *Sports Medicine*, 32, 633-653.
- Quarrie, K. L. & Hopkins, W. G. (2007) Changes in player characteristics and match activities in Bledisloe Cup rugby union from 1972 to 2004. *Journal of Sports Sciences*, 25, 895-903.
- Quarrie, K. L. & Hopkins, W. G. (2008) Tackle injuries in professional rugby union. *American Journal of Sports Medicine*, 36, 1705-1716.
- Quarrie, K. L., Hopkins, W. G., Anthony, M. J. & Gill, N. D. (2012) Positional demands of international rugby union: Evaluation of player actions and movements. *Journal of Science and Medicine in Sport*, 16, 353-359.
- Quinn, G. P. & Keough, M. J. (2002) *Experimental design and data analysis for biologists*. Cambridge, UK: Cambridge University Press.
- Rae, K., Britt, H., Orchard, J. & Finch, C. (2005) Classifying sports medicine diagnoses: A comparison of the International classification of diseases 10-Australian modification (ICD-10-AM) and the Orchard sports injury classification system (OSICS-8). *British Journal of Sports Medicine*, 39, 907-911.
- Rae, K. & Orchard, J. (2007) The Orchard Sports Injury Classification System (OSICS) version 10. *Clinical Journal of Sport Medicine*, 17, 201-204.
- Rauh, M. J., Macera, C. A., Ji, M. & Wiksten, D. L. (2007) Subsequent injury patterns in girls' high school sports. *Journal of Athletic Training*, 42, 486-494.
- Reilly, T. & Hardiker, R. (1981) Somatotype and injuries in adult student rugby football. *J Sports Med Phys Fitness*, 21, 186-91.
- Rhea, M. R., Alvar, B. A., Burkett, L. N. & Ball, S. D. (2003) A meta-analysis to determine the dose response for strength development. *Medicine and Science in Sports and Exercise*, 35, 456-464.

References

- Roberts, S. P., Stokes, K. A., Trewartha, G., England, M. & Hood, K. (2012) RFU Community Rugby Injury Surveillance Project: 2011-2012 Season Report. University of Bath.
- Roberts, S. P., Trewartha, G., England, M., Shaddick, G. & Stokes, K. A. (2013) Epidemiology of time-loss injuries in English community-level rugby union. *BMJ open*, 3, e003998.
- Roberts, S. P., Trewartha, G., Higgitt, R. J., El-Abd, J. & Stokes, K. A. (2008) The physical demands of elite English rugby union. *Journal of Sports Sciences*, 26, 825-833.
- Rogalski, B., Dawson, B., Heasman, J. & Gabbett, T. J. (2013) Training and game loads and injury risk in elite Australian footballers. *J Sci Med Sport*, 16, 499-503.
- Rondeau, V., Commenges, D. & Joly, P. (2003) Maximum penalized likelihood estimation in a gamma- frailty model. *Lifetime Data Analysis*, 9, 139-153.
- Rondeau, V., Filleul, L. & Joly, P. (2006) Nested frailty models using maximum penalized likelihood estimation. *Statistics in Medicine*, 25, 4036-4052.
- Rondeau, V., Mathoulin-Pelissier, S., Jacqmin-Gadda, H., Brouste, V. & Soubeyran, P. (2007) Joint frailty models for recurring events and death using maximum penalized likelihood estimation: Application on cancer events. *Biostatistics*, 8, 708-721.
- Rondeau, V., Michiels, S., Lique, B. & Pignon, J. P. (2008) Investigating trial and treatment heterogeneity in an individual patient data meta-analysis of survival data by means of the penalized maximum likelihood approach. *Statistics in Medicine*, 27, 1894-1910.
- van Rooyen, M., Yasin, N. & Viljoen, W. (2014) Characteristics of an 'effective' tackle outcome in Six Nations rugby. *Eur J Sport Sci*, 14, 123-9.
- Rosnow, R. L. & Rosenthal, R. (1989) Statistical procedures for the justification of knowledge in psychological science. *American Psychologist*, 44, 1276-1284.
- Rothman, K. J. (1990) No adjustments are needed for multiple comparisons. *Epidemiology*, 1, 43-46.
- Rothman, K. J., Greenland, S. & Lash, T. L. (2008) *Modern epidemiology*. Philadelphia, USA: Lippincott Williams & Wilkins.
- Ruedl, G., Abart, M., Ledochowski, L., Burtscher, M. & Kopp, M. (2012) Self reported risk taking and risk compensation in skiers and snowboarders are

References

- associated with sensation seeking. *Accident Analysis and Prevention*, 48, 292-296.
- Russell, M., West, D., Harper, L., Cook, C. & Kilduff, L. (2014) Half-time strategies to enhance second-half performance in team-sports players: a review and recommendations. *Sports Medicine*, 1-12.
- Ryan, J. M. & McQuillan, R. (1992) A survey of rugby injuries attending an accident and emergency department. *Irish Medical Journal*, 85, 72-73.
- Sanderson, S., Tatt, L. D. & Higgins, J. P. T. (2007) Tools for assessing quality and susceptibility to bias in observational studies in epidemiology: A systematic review and annotated bibliography. *International Journal of Epidemiology*, 36, 666-676.
- Scheuerman, S. B. (2012) The NFL concussion litigation: A critical assessment of class certification. *FIU L. Rev.*, 8, 81.
- Schootman, M. P., J. & Albright, J. P. (1994) Statistics in sports injury research. *Orthopaedic Sports Medicine*. Philadelphia, USA: WB Saunders.
- Sedeaud, A., Vidalin, H., Tafflet, M., Marc, A. & Toussaint, J. F. (2013) Rugby morphologies: "bigger and taller", reflects an early directional selection. *Journal of Sports Medicine and Physical Fitness*, 53, 185-191.
- Seward, H. & Orchard, J. (2004) AFL injury report 2003. *Sport Health*, 22, 1-20.
- Seward, H., Orchard, J., Hazard, H. & Collinson, D. (1993) Football injuries in Australia at the elite level. *Medical Journal of Australia*, 159, 298-301.
- Sharpe, S. R., Knapik, J. & Jones, B. (1997) Ankle braces effectively reduce recurrence of ankle sprains in female soccer players. *Journal of Athletic Training*, 32, 21-24.
- Shlens, J. (2009) A tutorial on principal component analysis. Cornell University.
- Shrier, I. & Steele, R. J. (2013) Classification systems for reinjuries: A continuing challenge. *British Journal of Sports Medicine*, 48, 1338-1339.
- Sinclair, M. R. & Cur, B. (2009) Protective equipment in rugby - Literature Review. BokSmart.
- Smart, D., Hopkins, W. G., Quarrie, K. L. & Gill, N. (2011) The relationship between physical fitness and game behaviours in rugby union players. *European Journal of Sport Science*, 14, S8-S17.

References

- Steffen, K., Emery, C. A., Romiti, M., Kang, J., Bizzini, M., Dvorak, J., Finch, C. F. & Meeuwisse, W. H. (2013) High adherence to a neuromuscular injury prevention programme (FIFA 11+) improves functional balance and reduces injury risk in Canadian youth female football players: A cluster randomised trial. *British Journal of Sports Medicine*, 47, 794-802.
- Stiles, V. H., James, I. T., Dixon, S. J. & Guisasola, I. N. (2009) Natural turf surfaces: The case for continued research. *Sports Medicine*, 39, 65-84.
- Stroup, D. F., Berlin, J. A., Morton, S. C., Olkin, I., Williamson, G. D., Rennie, D., Moher, D., Becker, B. J., Sipe, T. A., Thacker, S. B. & Grp, M. (2000) Meta-analysis of observational studies in epidemiology - A proposal for reporting. *Journal of the American Medical Association*, 283, 2008-2012.
- Strutzenberger, G., Cao, H.-M., Koussev, J., Potthast, W. & Irwin, G. (2014) Effect of turf on the cutting movement of female football players. *Journal of Sport and Health Science*, In Press.
- Struyf, A., Hubert, M. & Rousseeuw, P. J. (1997) Integrating robust clustering techniques in S-PLUS. *Computational Statistics & Data Analysis*, 26, 17-37.
- Sweet, T. W., Foster, C., McGuigan, M. R. & Brice, G. (2004) Quantitation of resistance training using the session rating of perceived exertion method. *Journal of Strength and Conditioning Research*, 18, 796-802.
- Swenson, D. M., Yard, E. E., Fields, S. K. & Comstock, R. D. (2009) Patterns of recurrent injuries among us high school athletes, 2005-2008. *American Journal of Sports Medicine*, 37, 1586-1593.
- Takemura, M., Okayama, A., Takazawa, Y., Maruyama, K., Toyama, M., Higashihara, J. & Furuya, M. (2011) Injury profile in the highest-level rugby union competition in Japan. *7th World Congress on Science and Football (WCSF)*. Nagoya University, Japan.
- Takemura, M., Schneiders, A. G., Bell, M. L. & Milburn, P. D. (2007) Association of ground hardness with injuries in rugby union. *British Journal of Sports Medicine*, 41, 582-7.
- Targett, S. G. R. (1998) Injuries in professional rugby union. *Clinical Journal of Sport Medicine*, 8, 280-285.
- Taylor, A. E., Fuller, C. W. & Molloy, M. G. (2011) Injury surveillance during the 2010 IRB Women's Rugby World Cup. *British Journal of Sports Medicine*, 45, 1243-1245.

References

- Taylor, A. E., Kemp, S., Trewartha, G. & Stokes, K. A. (2014) Scrum injury risk in English professional rugby union. *British Journal of Sports Medicine*, 48, 1066-1068.
- The Sports Office UK. The Rugby Squad. 2011; Available from: <https://www.therugbysquad.com/> [Accessed 04 October 2014].
- Therneau, T. (2012) Coxme: Mixed effects Cox models. R package version 2.3.
- Trewartha, G., Preatoni, E., England, M. E. & Stokes, K. A. (2014) Injury and biomechanical perspectives on the rugby scrum: A review of the literature. *British Journal of Sports Medicine*, bjsports-2013-092972.
- Twomey, D. M., Petrass, L. A. & Fleming, P. R. (2014) Abrasion injuries on artificial turf: A real risk or not? *South African Journal of Sports Medicine*, 26, 91-92.
- Ullah, S., Gabbett, T. J. & Finch, C. F. (2012) Statistical modelling for recurrent events: An application to sports injuries. *British Journal of Sports Medicine*, 46, 1-9.
- Unold, O. (2011) Machine learning approach to model sport training. *Computers in Human Behavior*, 27, 1499-1506.
- Vaupel, J. W., Manton, K. G. & Stallard, E. (1979) Impact of heterogeneity in individual frailty on the dynamics of mortality. *Demography*, 16, 439-454.
- Verrall, G. M., Slavotinek, J. P., Barnes, P. G., Fon, G. T. & Spriggins, A. J. (2001) Clinical risk factors for hamstring muscle strain injury: A prospective study with correlation of injury by magnetic resonance imaging. *British Journal of Sports Medicine*, 35, 435-439.
- de Visser, H. M., Reijman, M., Heijboer, M. P. & Bos, P. K. (2012) Risk factors of recurrent hamstring injuries: A systematic review. *British Journal of Sports Medicine*, 46, 124-130.
- Wade, C. E. (1988a) Sports injury research. What is the question? *Am J Sports Med*, 16 Suppl 1, S38-42.
- Wade, C. E. (1988b) Sports injury research. What is the value of the case-control study? *Am J Sports Med*, 16 Suppl 1, S53-4.
- Waldén, M., Atroshi, I., Magnusson, H., Wagner, P. & Hägglund, M. (2012) Prevention of acute knee injuries in adolescent female football players: Cluster randomised controlled trial. *BMJ*, 344, 1-11.

References

- Waldén, M., Hägglund, M. & Ekstrand, J. (2005) Injuries in Swedish elite football— A prospective study on injury definitions, risk for injury and injury pattern during 2001. *Scandinavian Journal of Medicine & Science in Sports*, 15, 118-125.
- Warren, B., Cavanagh, B., Douglas, W., Donovan, T. F., Morton, J. P. & Close, G. L. (2014) Quantification of training load, energy intake and physiological adaptations during a Rugby pre season: A case study from an Elite European Rugby Union Squad. *The Journal of Strength & Conditioning Research*, In Press.
- Wassell, J. T., Wojciechowski, W. C. & Landen, D. D. (1999) Recurrent injury event-time analysis. *Statistics in Medicine*, 18, 3355-3363.
- Weaving, D., Marshall, P., Earle, K., Nevill, A. & Abt, G. (2014) Combining internal-and external-training-load measures in professional Rugby League. *IJSPP*, 9, 905-912.
- Webborn, N. (2012) Lifetime injury prevention: The sport profile model. *British Journal of Sports Medicine*, 46, 193-197.
- Wei, L. J., Lin, D. Y. & Weissfeld, L. (1989) Regression-analysis of multivariate incomplete failure time data by modeling marginal distributions. *Journal of the American Statistical Association*, 84, 1065-1073.
- Welsh, A. H. & Knight, E. J. (2014) "Magnitude-Based Inference": A statistical review. *Medicine and Science in Sports and Exercise*, In Press.
- Williams, S., Hume, P. A. & Kara, S. (2011) A review of football injuries on third and fourth generation artificial turfs compared with natural turf. *Sports Medicine*, 41, 903-23.
- Wilson, G. V. & Kerr, J. H. (1999) Affective responses to success and failure: A study of winning and losing in competitive rugby. *Personality and Individual Differences*, 27, 85-99.
- World Health Organisation. International Classification of Diseases. 2010; Available from: <http://apps.who.int/classifications/icd10/browse/2010/en> [Accessed 15 December 2012].
- Wu, J., Liu, H., Duan, X., Ding, Y., Wu, H., Bai, Y. & Sun, X. (2009) Prediction of DNA-binding residues in proteins from amino acid sequences using a random forest model with a hybrid feature. *Bioinformatics*, 25, 30-35.
- Yukelson, D. (1997) Principles of effective team building interventions in sport: A direct services approach at Penn State University. *Journal of Applied Sport Psychology*, 9, 73-96.

References

Zhang, T., Ramakrishnan, R. & Livny, M. (1996) BIRCH: An efficient data clustering method for very large databases. *Proceedings of the 1996 ACM SIGMOD International Conference on Management of Data*. New York, USA, ACM.

APPENDIX A: Severity data for each injury diagnosis grouping (Chapter 5)

Table A.1 Mean, standard deviation and median severity [days] of injury diagnosis groupings for seasons 2005/06 to 2012/13

Injury diagnosis grouping	Mean severity	SD	Median severity
Achilles tendon injury	42	77	10
ACL injury	231	109	232
Acromioclavicular joint injury	18	23	9
Adductor muscle injury	14	24	8
Ankle joint capsule sprain	10	14	5
Ankle lateral ligament injury	16	21	8
Calf muscle injury	14	16	9
Cervical disc injury	74	66	43
Cervical facet joint injury	8	12	5
Cervical nerve root injury	19	25	8
Concussion	12	21	8
Costochondral/ sternal injury	13	11	11
Dislocation/instability shoulder	78	63	79
Foot or toe joint sprain	17	25	8
Fracture arm	67	30	61
Fracture foot	82	84	38
Fracture tibia/fibula	100	75	92
Fracture wrist/hand	39	25	33
Haematoma buttock/groin	10	18	6
Haematoma calf or shin	7	7	4
Haematoma foot or ankle	10	22	5
Haematoma shoulder	7	5	6
Haematoma thigh	7	18	4
Haematoma, knee	9	19	4
Hamstring muscle injury	20	28	12
Head/facial fracture	27	23	22
Head/facial laceration	9	10	6
Hip flexor/quadriceps muscle injury	11	13	6
Inferior tib-fib syndesmosis injury	39	40	27
Inguinal canal injury	41	30	33
Knee cartilage/degenerative injury	55	81	26
Knee joint sprain/jar	13	23	6
Lumbar disc, nerve or canal injury	39	68	12
Lumbar facet joint injury	8	9	5
MCL injury	31	30	23
Other injury arm/elbow	24	34	6
Other injury lumbar/groin/hip/buttock	18	32	7

Appendices

Other injury thorax or abdomen	33	38	15
Other injury wrist/hand/finger	19	27	6
Other injury, head region	10	15	5
Other injury, knee	15	23	7
Other injury, lower leg, foot or ankle	19	30	9
Other injury, neck region	15	40	5
Other injury, shoulder region	37	58	10
Other injury, thorax or abdomen	15	19	9
Patella tendon injury	28	55	8
PCL/LCL injury	48	65	30
Quadriceps muscle injury	12	11	10
Rib fracture/contusion	11	16	7
Rotator cuff injury/ shoulder impingement	34	45	11
Soft tissue injury, lumbar region	6	5	4
Stress fracture foot	81	65	55
Thoracic facet joint injury	6	7	5
Overall	23	42	9

APPENDIX B: Participant information sheet and consent form (Chapter 6)

An investigation of the incidence and nature of non-time-loss injuries, time-loss injuries, infections and abrasions sustained on artificial and natural turf in professional Rugby Union.

Principal Investigators: Keith Stokes and Grant Trewartha

Lead researcher: Sean Williams

You are invited to take part in a research study to determine whether there is a difference in the incidence, types and causes of injuries sustained by Premiership rugby players playing on artificial turf compared with natural turf. The study is fully supported by the Rugby Football Union, Premier Rugby Ltd and the Rugby Players Association. Before deciding whether to take part, it is important that you understand why the study is being undertaken and whether it will affect you. Take time to read the following information carefully; if there are any aspects of the study that you do not understand, please discuss them with a member of your medical team or contact us for further information. When you have read and fully understood the information and you wish to be included in the study, you will be asked to sign a Player Consent Form prior to commencing the study. The Principal Investigator responsible for the study is Dr Keith Stokes at the University of Bath and he has been/is involved in similar injury surveillance studies in rugby union.

Background to the study

The aim of this study is to determine whether there is a difference in the incidence, types and causes of injuries sustained by Premiership rugby players playing on artificial turf compared with natural turf. The study will run throughout the 2013-2014 season. Injury surveillance studies of this type provide data that help to monitor levels of injury risk and to develop injury prevention, treatment and rehabilitation programmes in rugby union.

What does the study involve?

After games involving Saracens RFC, any abrasions identified by medical personnel or research officers from the University of Bath will be assessed using scales relating to the size and depth of the abrasions. Non-Saracens players only will also be invited to complete an online questionnaire during the week following the match. All injuries and infections secondary to abrasions and grazes incurred during these matches will also be recorded as part of the on-going English Professional Rugby Injury Surveillance Project. This data will be analysed by researchers in the Department for Health at the University of Bath

Who is being asked to participate in the study?

We are requesting the participation of all players who take part in matches involving Saracens RFC during the 2013-2014 season.

Do players have to take part?

Participation in the study is voluntary. You do not have to take part in the study but the more players who take part, the more comprehensive the data will be. If you decide to take part, you must sign a consent form that confirms you have been provided with this information and you agree to be included in the study. You are free to withdraw from the study by contacting us at any time without giving a reason.

What do I have to do?

Following the match, a research officer from the University of Bath will assess any abrasion injuries incurred during match-play using scales relating to the size and depth of the abrasions; these will be explained clearly to you at the time of collection. If no abrasion injuries have been incurred, you will not be required to provide any information. Players will also be invited by the RPA to complete an online questionnaire in the week following the fixture against Saracens. This will be used to assess perceived levels of muscle and joint soreness compared with games on natural turf as well as asking for feedback about the experience of playing on artificial turf.

Players from a sample of clubs will be invited by the RPA to provide a daily assessment of muscle soreness via SMS / text for 5 days after a match played at Allianz park and a match played (on natural grass) either a week before or week after that match.

Appendices

Players from a sample of clubs will be invited by the RPA to provide a daily assessment of muscle soreness via SMS / text for 5 days after a match played at Allianz park and a match played (on natural grass) either a week before or week after that match.

Are there any risks from taking part?

You will not be doing anything in addition to your normal rugby activities with the club.

Will information about my injuries be kept confidential?

In accordance with the Data Protection Act, we must obtain your permission to collect information about your injuries during the course of this study. To maintain anonymity, all questionnaires and other data collection sheets will utilise code numbers in place of names for individuals and their clubs. The results will not be used in such a way as to identify or make obvious any individual or club.

What will happen to the data obtained from the research study?

The data collected will be collated and analysed by researchers at the University of Bath in order to produce original articles in peer reviewed journals, conference presentations, and reports prepared for individuals involved in the game (i.e. rugby players, coaches, conditioning and medical staff).

Player consent form

I confirm that I have read and understood the player information sheet for the above study and that I have had an opportunity to ask questions.

I agree to take part in the above study and give my consent for doctors, physiotherapists and fitness/conditioning staff to supply medical and training information to the University of Bath. I acknowledge that such information will only be used for research, statistical and other analysis purposes, and that personal references shall not be made in any report or other published material.

I understand that all the information provided on my injuries and training will be treated in strict confidence and will remain anonymous.

I understand that I have the right to withdraw from this study at any stage and that I will not be required to explain my reasons for withdrawing.

Name

Date

Signature

OFFICE USE ONLY

CLUB

PLAYER REGISTRATION NUMBER

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APPENDIX C: Logistic regression analyses for relationship between training load measures and injury risk (Chapter 8)

Table A.2 Results of backwards stepwise logistic regression analysis for the training load measures highly correlated with component one of the PCA. Presented results are for the best-fitting model, based on AIC value (3410). The exponentially-weighted moving average variable was selected as the surrogate representative measure for this component

Training load measure	Estimate	<i>P</i> -value
Exponentially-weighted moving	0.378	0.0000000000000004
1 week cumulative load	0.368	0.0009
Strain	-0.333	0.004

Table A.3 Results of backwards stepwise logistic regression analysis for the training load measures highly correlated with component two of the PCA. Presented results are for the best-fitting model, based on AIC value (1865). The week-to-week change variable was selected as the surrogate representative measure for this component

Training load measure	Estimate	<i>P</i> -value
Week-to-week change	-0.336	0.003
Training stress balance	-0.087	0.08

APPENDIX D: Participant information sheet and consent form (Chapter 8)



The English Professional Rugby Injury Surveillance Project Player Information Sheet



The influence of training load on injury and illness in elite rugby union

Principal Investigator: Keith Stokes

Other Investigators: Matt Cross, Grant Trewartha, Sean Williams, Simon Kemp

You are invited to take part in a research study that will investigate training and match loads as a risk factor for injury and illness in elite rugby union. The study is fully supported by the Rugby Football Union, Premiership Rugby and the Rugby Players' Association. This study will be fully aligned with the RFU professional rugby injury surveillance project, this will allow for the collection of time-loss match and training injuries during the competitive season for use in this study. Before deciding whether to take part, it is important that you understand why the study is being undertaken and how it might involve you. Take time to read the following information carefully; if there are any aspects of the study that you do not understand, please discuss them with a member of your medical team or contact us for further information. When you have read and fully understood the information and you wish to be included in the study, you will be asked to sign a consent form.

Background to the study

A player or team's training load has been highlighted as a potential risk factor for injury in other collision sports. Although a small number of studies have investigated training duration as a risk factor for injury in rugby union, at the time of writing no publications could be found that combined training duration and intensity to investigate the effect of training load on injury occurrence and severity. Without this information it is difficult to determine best practice for calculating appropriate training loads for the season on a week to week basis. It is thought that, in the long term, training load and the accumulation of training load over time may also play an important role in the management of overtraining and subsequently career longevity. This study will allow for a better understanding of the management of training load throughout a competitive season and will also consequently contribute to improving player welfare.

The aim of this study is to determine the relationship between training load and the incidence/severity of injury and illness. This particular study will aim to look at whether weekly training load, accumulation of load across a 2, 3 or 4 week period, weekly changes in load and training variability within a week are risk factors for injury and/or illness. The information that this study provides will be an important and valued component in the continued development of training programmes for coaches. Data will be collected for this study during one season (2013/14).

What does the study involve?

Daily training load, match load and time-loss injury and illness data will be collected for all full-time contracted players that participate in the study.

You will be asked to complete a questionnaire at the start of the season. This questionnaire will be included as part of your baseline information (date of birth, height, weight) that is provided at the start of the season by medical personnel.

To be able to calculate training load, you will be asked to submit an RPE (Rating of Perceived Exertion) score (on a scale of 1 to 10) within 30 minutes after the end of each training session and match. The strength and conditioning coach at the club will then submit the duration of each session so that this can be matched to each RPE score to allow a value for training/match load to be calculated.

Your time-loss injury data such as incidence, type, severity and causation will be reported by your medical staff using a secure online only medical system. In addition to the collection of injury the RFU English Professional Rugby Union Injury Surveillance Project will also allow for the collection

For further information, or if you have any questions, contact Matt Cross, University of Bath.
e-mail: rfu-prem-audit@bath.ac.uk



The English Professional Rugby Injury Surveillance Project Player Information Sheet



of illness from season (2013-2014), this illness data will be included in this study. For the purpose of this study illness will be defined as

'An occasion after medical consultation that leads to the withdrawal from full training or match play for more than 24 hours that can be reported using illness codes available from a modified OSICS 10 medical coding system in Rugby Squad.'

This data will be analysed by researchers in the Department for Health at the University of Bath.

Who is being asked to participate in the study?

All first team squad players at English Premiership rugby clubs are being asked to take part in the study.

Do I have to take part?

Participation in the study is voluntary. You do not have to take part in the study but the more players who take part, the more comprehensive the data will be. If you decide to take part, you must sign a consent form that confirms you have been provided with this information and you agree to be included in the study. You are free to withdraw from the study by contacting us at any time without giving a reason.

Are there any risks from taking part?

There are no risks associated with this project over and above your normal rugby activities with the club.

Will information about my injuries be kept confidential?

In accordance with the Data Protection Act, we must obtain your permission to collect information about your injuries during the course of this study. All information collected in the study is recorded and stored anonymously using a player identification code on a database at the University of Bath.

What will happen to the data obtained from the research study?

The data collected will be analysed by researchers at the University of Bath to produce summary information about the influence of training load on the incidence and severity of injury and/or illness. This information may be used by the RFU/Premiership Rugby/RPA for the formation of guidelines for the management of training load in the future.

For further information, or if you have any questions, contact Matt Cross, University of Bath.
e-mail: rfu-prem-audit@bath.ac.uk



The English Professional Rugby Injury Surveillance Project Player Information Sheet



Player consent form

I confirm that I have read and understood the player information sheet for the above study and that I have had an opportunity to ask questions.

I agree to take part in the above study and give my consent for doctors, physiotherapists and fitness/ conditioning staff to supply medical and training information to the University of Bath. I acknowledge that such information will only be used for research, statistical and other analysis purposes, and that reference to individuals shall not be made in any report or other published material.

I understand that all the information provided on my injuries and training will be treated in strict confidence and will remain anonymous.

I understand that I have the right to withdraw from this study at any stage and that I will not be required to explain my reasons for withdrawing.

Name

Date

Signature

OFFICE USE ONLY

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